THE UNIVERSE SURVEYED

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PHYSICS CHEMISTRY ASTRONOMY GEOLOGY

by

HAROLD RICHARDS

With a Preface by

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PREFACE

ONE of the primary functions of any modern educational system is to give those exposed to its influence an opportunity to see themselves in true perspective in relation to the sweep of time and the stretch of space. There is an increasing tendency to do this by means of " survey courses " which cut across the traditional boundaries between the separated segments of curricular subjects. The success with which such surveys have been crowned is due in part to the fact that departmental frontiers are manifestly artificial, whereas the unified treatment is more in harmony with the fundamental unity of nature. It is also partly due to the fact that whereas analysis is essential in research, synthesis is essential in teaching. Moreover, it is now apparent that a general view is not necessarily a superficial view but may lead unerringly to a deeper understanding of the ways of the universe than a highly specialized approach can achieve.

In dealing with any general survey of our knowledge of the physical world, however, it is unusual to find a teacher or an author who combines the necessary familiarity with the countless minutiae of detailed information, streaming from the numerous research laboratories where investigators are rapidly pushing outward the frontiers of the physical sciences, with the equally necessary ability to express himself lucidly and accurately in simple and interesting terms. It has been extremely refreshing, therefore, to discover in Professor Richards' manuscript the handiwork of one who has an unmistakable flair for exposition and a truly scientific attitude toward his task. His use of vivid similes and arresting word-pictures is excellent pedagogy, well qualified to stimulate the interest which precedes the acquisition of knowledge. Espe-

cially fine is the subtle distinction frequently drawn between fact and theory, observational data and hypothetical explanation, well established principle and tentative inference. Scientific knowledge is presented as a vital, growing factor and the reader cannot fail to catch something of the spirit of adventure and realize to some extent the opportunities for creative activity which are to be found along every sector of the scientific frontier.

This book is eminently suited as a text for the junior college or freshman year course designed to give a general introduction to the physical sciences. The balance between the several fields of physics, chemistry, astronomy and geology is nicely adjusted. No great friendliness with higher mathematics is presupposed in its readers. Only the necessary minimum of technical terms is used. Anyone who reads these pages thoughtfully will finally close the book with a sense of having experienced an exciting and informing excursion into intellectual territory that has been transformed by it from a complex and mysterious region into an ordered and charted countryside where he can feel very much at home.

KIRTLEY F. MATHER

Harvard University
May, 1937

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HAROLD RICHARDS

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Chapter 1

INTRODUCTION: SCIENCE AND THE MODERN WORLD

WHAT the serious student seeks primarily is a way of life. He wants to know what constitutes a satisfying and worth-while life, and how to live it. In self-defense he fortifies himself with knowledge of his environment, so that he will not be completely at its mercy; and out of self-respect he tries to become sufficiently useful to society to justify his consumption of goods and services. But beyond these practical ends he aspires to something more. He wants to express himself in some medium or other. He wants to understand, and perhaps help to solve, the problems of civilization. And for his own satisfaction he seeks to know his relation to the universe, the purpose of existence, and his own importance in the scale of space and time.

What has science to do with that far-reaching program? One of the objectives is orientation in one's environment. Our environment may be divided roughly into the material and the spiritual — into the world of matter, both animate and inanimate, and the world of thought. Science deals directly with both those worlds. Modern civilization owes largely to science its acknowledged success in dealing with the material world, and that success has caused the ideas of science to wield a great influence in shaping the thinking of the age.

The Conquest of Nature

In the three centuries since Galileo the success of the sciences in dealing with matter has placed so much power in the hands of

mankind that our environment has been modified faster than civilization has adapted itself to the new ways of living. Man has been transformed from a creature who cowered in superstitious fear before the lightning, to one who can manufacture lightning himself.

One says "Let there be light" and there is light, merely for the flicking of a tumbler switch. It is barely more than a century since that great English physicist, Michael Faraday, discovered the principle which we apply in generating all the electricity that flows through the power lines of the world. When, in 1831, Faraday reasoned that if electricity in motion produced magnetism, then magnetism in motion should produce an electric current, and then tried the experiment, he held in the hollow of his hand more power than Alexander the Great could ever have hoped to wield, or Julius Caesar, or Napoleon, or any of our modern dictators. For what military genius or statesman of history has been able to enmesh the world with silent power, to contribute to mankind the working equivalent of many slaves per inhabitant?

It is scarcely necessary to elaborate. One has only to look around to discover how wide the field of science is, how numerous its applications in daily life. Here we are interested especially in the physical sciences. One lifts the receiver and hears a voice. If suitable instructions are given, that voice may be followed by another from the opposite side of the earth, a voice singled out by applied physics from the two billions of human voices which sound in our terrestrial bedlam. One goes to the motion picture house for an evening's relaxation, and there he witnesses marvels which could not have existed if the laws of electricity, sound, light, heat, and chemical action had not been discovered. If a motion picture could have been displayed at the time of the first Congress of the United States, with the mechanics of projection concealed, many of the

witnesses might have believed that they beheld a miracle. Some light leaves the star Arcturus in 1893 while one world's fair is in progress in Chicago, and forty years later we catch a tiny fraction of that same light and use it, after amplifying its electrical effect many millionfold, to open the gates of another world's fair in the same city.

Indeed, so great has man grown in his power to modify and control his environment that today we sometimes hear talk of a holiday in applied science, a breathing space, supposedly, for the hard-pressed experts in applied economics and statecraft. In this suggestion one may see, if he likes, the crowning tribute to science. Yet science cannot evade responsibility for many of our social and economic problems. Behind electric power, behind mass production in industry and the multiplied bounty of our fields lie physics and chemistry and biology. Science enables massed populations to live in highly restricted areas. Difficulties of social adjustment arise. Thanks to scientific nutrition, sanitation, and bacteriology, plagues no longer cut the Gordian knot by wiping out vast sections of humanity. The swift transportation and communication made possible by physics and chemistry have revolutionized internal economy and added international complications. In a word, science has come bringing long life, leisure, plenty, kaleidoscopic possibilities of full living — sweet words, but the handling of this bounty is difficult.

Should the physical sciences take a holiday? The argument in support of the idea involves the question of unemployment. Protest against the labor-saving inventions which result from the discoveries of physical science is as old as the steam engine.

If progress in science were merely a matter of walking into a laboratory and saying "Go to, I will now make a discovery," a few might be willing to adopt a holiday as a temporary expedient;

though wilfully to retard the growth of knowledge and thus limit man's outlook and his power over his environment would seem to be a gospel of defeatism. But scientific discoveries are not made to order. Roentgen discovered x-rays without knowing in advance what he might find, or whether he would find anything. Society must take its Roentgens and Pasteurs, its Faradays and Galileos and Lavoisiers, when it can get them.

Incidentally, our example illustrates another point. Entirely apart from the benefits which the x-ray tube has brought to humanity—the accurate diagnosis of disease, the localization of bullets and shrapnel, the improvements in bone-setting, the avoidance of needless amputations, the treatment of diseases, the great wealth of new knowledge of matter and electricity which has been won by using x-rays in scientific research—another benefit, one of interest to the economist, has resulted from Roentgen's discovery. The manufacture, distribution, and operation of x-ray tubes and their accessories have created new employment for thousands. That is the history of scientific progress. Despite temporary dislocations, the net result of new discoveries is to open new avenues for work.

No, the way of escape seems to lie not in the direction of less science but of more science. Shall man renounce the possibility of a larger life because he cannot learn to use what he has sought and won through his conquest of nature? One might perhaps wish for loftier motives in the hearts of men, but need we wait for human nature to change? Only man's own behavior stands between him and the full fruits of his power over his environment. Science has gained its ends without changing the laws of the materials it works with. Can man apply that same method to himself? Are there laws that govern human behavior, comparable to the laws which the physicist and the chemist have discovered?

The question would take us far afield. We pause merely to point out that to the physical sciences we owe both the concept of natural law and the technique of looking for it.

The Philosophy of Science

What is responsible for the commanding position of science in the modern world? What are the ideas and the methods which have so effectively transformed our environment and helped to shape our thinking? The underlying philosophy was not an automatic growth, universally accepted. It was discovered, and it was established at the cost of centuries and blood.

The philosophy of science is one of acceptance — but not supine acceptance. The scientist finds out by patient observation and reasoning how matter behaves, then sets the scene so that those natural principles of action will lead to the desired result.

For example, it is natural for water to run downhill. This is a consequence of the tendency of water to flow in the direction of the greater pressure. We are at liberty to make the greater pressure act uphill towards the top of a skyscraper if we choose. Again, it is natural for heat to flow from a hotter to a colder body. It is equally natural for liquids to lose heat when they evaporate. The scientist discovers this, so today in our mechanical refrigerators we cool objects below the temperature of their surroundings by applying the same cooling action which anyone can discover for himself by waving a moistened finger in the air. Heat is removed from the colder body and given up to the warmer surroundings; but at no stage in the process does heat actually flow from colder to hotter. The scientist has simply pitted one natural action against another, so to speak, and gained his end. His philosophy may be one of acceptance, but he gains his ends!

From those earlier moments in childhood when one worries because rain upsets the picnic plans, to that later period in old age when those who have not improved their philosophy are perhaps still troubled by the apparent indifference of the physical universe to man's aspirations, one lives in a world of matter. How can one form a sound philosophy of life without knowing something of the natural scheme which, willy-nilly, determines the framework in which ideals and imagination must thread their way? To the true scientist, adjusted to his world, philosophically secure, it does not occur to worry because the laws of nature have not some different form. He finds out what is, he rejoices in each new discovery, he is glad to be dealing with a universe so marvelously constructed that after more than two thousand years of genius there are still new truths to be revealed. Cannot everyone steal for himself some of this philosophy, this peace?

Science does not deal with questions of ultimate aim and purpose. It does not deal with beauty, taste, goodness — but only with true and false. The astronomer may feel that in revealing the hidden glories of the stars he is making a contribution to beauty, but he does not ask to be installed as arbiter of aesthetics. The mathematician, that indispensable ally of the exact sciences, creates a beauty all his own, the beauty of perfect consistency; but he, too, passes no judgments. Science may feel that in bringing to light the complicated wonders of the universe, the beautifully related secrets of atoms and space, it is providing religion with material well calculated to inspire awe and reverence and to lift man's eyes above the sordid, but it makes no claims. It merely continues to find demonstrable truth, which carries its own credentials.

In short, science has discovered, at great cost, that only by relegating questions of ethics and aesthetics to one side during working hours can one find the truth about the material world. Yet,

call the roster of great names in science. Study, for example, the lives of Copernicus, Kepler, Galileo, Harvey, Descartes, Newton, Leibnitz, Linnaeus, Priestley, Dalton, Agassiz, Darwin, Helmholtz, Pasteur, Kelvin, Huxley. Read of Madame Curie, Einstein, Eddington, Jeans, Millikan, the Comptons. Surely, to study these people is to discover the loftiness of purpose with which the builders of science have striven to increase man's store of knowledge.

Science boldly confronts the universe and faces the facts. Within its own field it acknowledges no authority higher than observation and reason. For every one of us, it is a salutary experience to discover that there is a substratum of hard reality, brute facts which cannot be changed to suit man's whims. Oh, "the ugly fact that destroyed the beautiful theory!"

Listen to William Harvey dedicating, in 1628, his epochal work on the circulation of blood: "My dear colleagues, I had no purpose to swell this treatise . . . by quoting the names and writings of anatomists . . . , because I profess both to learn and to teach anatomy . . . not from the positions of philosophers, but from the fabric of nature."

And listen to William James writing a letter to his brother Henry James, the novelist: "I have to forge every sentence in the teeth of irreducible and stubborn facts."

One can almost feel the anguish with which the great psychologist rejects ideas because they do not square with observation. James' statement is remarkable. The familiar ideal of truth is there; but there is also the suggestion of painful struggle between fact and preconceived ideas. No branch of learning has achieved the transition from philosophy to science without an inner conflict. But the long traditions and accumulated wealth of the older sciences, of physics, chemistry, astronomy, and mathematics, have been available to speed the progress of the newer sciences, and

nowadays the leading workers in all fields worthy of the name of science have attained impartiality, a state of mind in which they do not care how the experiment turns out so long as they find the truth.

It should be remarked, in passing, that this ideal is not the peculiar property of the scientist. The novelist who is a genuine artist holds precisely the same ideal. He portrays the truth and sheds no tears.

Scope of the Physical Sciences

Physics, chemistry, astronomy and geology are the basic physical sciences. Much of what has been said suggests what physics and chemistry deal with. Both are interested in the structure and behavior of inanimate matter. Physics deals with force, which can move mountains, elevators, battleships, blood corpuscles. It studies the mechanical principles which can be applied to multiply the effects of forces. It deals with motion itself, the motion of air, water, stars, artillery projectiles, airplanes, electrons, and anything else that moves. It deals with energy in all its manifestations: with heat, light and color, sound, magnetism, electricity, x-rays, radio, cosmic rays. Wherever inanimate matter is, there is the hunting ground of physics and chemistry. The earth and the dewdrop, a planet or a soap bubble, the human body or a star—all contain molecules and atoms, electrons and protons, and with these and their many actions the physical sciences deal.

In building its structure, physical science has drawn freely on mathematics, sometimes manufacturing new mathematics, as Newton did, when the supply seemed inadequate. Otherwise, it is fundamental and self-sufficient. Nothing comes between physics and its subject matter. It goes straight to nature. It comes to grips

with reality itself. The methods of seeking and testing truth which the physical sciences established have been accepted as valid and widely applied in many fields. From the first discoveries crude measuring instruments resulted; these led to new discoveries, which in turn suggested new methods. So our knowledge has grown, feeding on itself, and still grows by leaps and bounds.

Because of their fundamental character, physics and chemistry are closely related to many other branches of knowledge. The astronomer's star, for example, and the geologist's rock, are both to be explained in terms of chemistry and physics. It matters not that one is in the heavens and the other in a gorge. Meteorology, the science of the weather, though usually classified as a branch of geology, is sometimes called the physics of the atmosphere.

The boundaries between subjects are breaking down as knowledge grows. It is difficult to draw the line between chemistry and physics. Formerly there was a gentlemen's agreement whereby the physicist stayed outside the molecule while the chemist roamed within; but electricity, the physicist's proper tool, has recently led him straight into forbidden territory, the heart of the atom, which in many cases he has taken apart.

One crude distinction, practical but rough, can be made. Chemistry is interested in substances without regard to size or shape, and with their combinations or disintegrations to form other substances. The physicist has a greater interest in the behavior of objects which are composed of the chemist's substances. For example, the physicist would stress the action of a glass camera lens in focusing light to form an image, while the chemist emphasizes the composition of the glass and the development of the photographic film. But the physicist is also interested in glass as glass, its electrical insulating properties, its expansibility under heating, its ability to disperse white light into its component colors. Recent

progress has dulled the edges of the distinctions which were formerly made.

The sciences which deal with living matter necessarily involve chemistry and physics; for disembodied life has never been found. Being alive does not relieve matter of the necessity of obeying the laws of chemistry and physics. Life is a property, not yet explained, of certain forms of matter, and within that living matter heat and electricity are at work, and familiar mechanical and chemical actions are taking place.

The basic physical sciences are exact. They have gone far beyond the stage of mere qualitative description and classification. Numerical data alone do not form an exact science. An illustration from the astronomy of the 16th century will make the nature of exact science clear. Tycho Brahe, the eccentric Danish astronomer, spent his life measuring the positions of the planets with hitherto unparalleled skill. At his death in 1601 he possessed hundreds of numbers, a bookful of numbers, the most voluminous and accurate planetary data that had ever been assembled. His book told where certain planets at certain stated times *had stood*. It was history, the first step in exact science. But the relationships were unknown. One could not predict with certainty from Tycho's numbers where the planets *would stand*.

Tycho's pupil Kepler inherited the book. After years of patient study he discovered the laws that lay implicit in the numbers. He found what we now call Kepler's laws of planetary motion, three laws which can be printed in a few inches yet contain vastly more information than Tycho's whole book. With the aid of those laws one can both calculate the past and predict the future movements of the planets.

Physical science gives more than history, something far beyond mere patient description. It shows the connections and relations,

it reveals the laws of inanimate nature. Yet even with the laws at hand, the scientist cannot rest. Why? he asks. Why, for example, do the planets move in accordance with Kepler's laws? A planet cannot violate the law and pay a fine. What inner or outer compulsion does it obey as it swings so surely, with never a misstep, through the heavens?

But let us not anticipate too far. Often another, more fundamental law is discovered, of which the one in question is a necessary consequence and so is said to be explained. Then we dive deeper in the sea of truth. In the end we are in very deep waters. Indeed, there come moments when we seem to be looking through the bottom of the sea, peering as through a glass-bottomed boat at the bare stripped framework of the universe. In those rare moments we seem to find ourselves face to face with physical reality itself, a reality unified yet so strange, so utterly different from the concrete impressions yielded by our senses, that the scientist may be pardoned his license if he turns poet or philosopher, if that be his bent, and talks of infinity, and of the ultimate fate of a star, and the roles that free will and chance play, respectively, in the universe. But he will warn you if he ever leaves the solid ground of surely ascertained fact, so that you may match your opinions against his.

A Look Ahead

But these early pages are not the place to try for the ultimate, or to consider what one may and may not think about his relation to the universe of matter. A mind attempting to think without facts reminds one of a concrete mixer churning away with no sand or cement in the hopper. In this book there must be plenty of facts — but which facts, and how to arrange them, is a problem.

If the time should ever come when physics is a completed science, its laboratory gown laid away and the last secret of the physical universe committed to writing, there will be two sorts of physics books to be written. One, of historical and human interest, will recount the long story of man's devious gropings after truth, a story in which the history of brave struggles and splendid flights of genius will be mingled with tales of errors and strange interludes to regale the student of that imagined epoch. The other work will be a model of deductive writing. It will begin with a description of the actual structure of either matter or energy, whichever has gained priority. This will be expressed, no doubt, in a single mathematical equation. The laws of physical action will then be deduced. The sparkling of a diamond, the flight of a projectile, the pulsations of a variable star, and all other physical actions will be fitted neatly into their logical places in that hypothetical text, each shown to be a necessary consequence of the basic structure or equation of the ultimate physical reality.

Neither of those ideals will be aimed at exclusively here. The truth about nature could of course be culled from among the errors which would fill so many pages if the historical method were used, and the reader would gain a basis for appraising and understanding the present. One would also come to see why science has been forced to give up many ideas which once seemed reasonable. The world at bottom is vastly different from the simple concepts which we get by kicking a stone (the act by which Samuel Johnson thought to discredit Bishop Berkeley's philosophy of sensational idealism). But the story would be very long. It would not present the actual truth in the neat logical order of the analytical method. It would not reveal so clearly how it is that apparently unrelated phenomena of nature are really closely connected. Experience shows that to see the relation of one action or event to

another does more to make life's panorama interesting and significant than to know isolated facts.

So we adopt a compromise. Without attempting to make the whole one tightly knit structure of logic we shall divide our study into a number of packages. Within each unit the relation of one fact of nature to another should be looked for. In the first unit, for instance, it may surprise the reader to find that the falling of a stone and the red of the setting sun are related. Many facts will be omitted in order that the account may flow swiftly and the logical connections stand out clearly.

Finally, the reader is asked to remember that this is not an encyclopaedia. The shelves of the library hold material for every interest, whether of biography, or the history of ideas, the technical details of the practical applications of modern science, or the philosophical implications of our knowledge. A book of this character must be looked on as an introduction to a *kind of thinking* which has wrought wonders and to a body of knowledge so great that a sampling must suffice for the present. Above all, let us look for relationships. The world is a dull flat place for those who see every phenomenon as an isolated happening, unrelated to anything else. Let us hope that in the end we may have a frame in which to set the knowledge which we have gained.

UNIT 1

THE EARTH AS AN ASTRONOMICAL BODY AND OUR NEIGHBORS IN SPACE

Chapter 2

FALLING

WHY do we fall when the foot-bridge breaks under us? A simple question, perhaps, to the modern mind; yet the history of man's serious attempts to answer it spans two thousand years and the answer itself, when finally discovered, was found to link us with the stars.

Aristotle's Ideas Concerning Up and Down

Why do bodies fall? We go back to Aristotle, the Greek philosopher of the fourth century B.C., for one of the earliest discussions of the question. Aristotle taught Alexander the Great; he studied under Plato in the Golden Age which Pericles had bequeathed to Greece, and grew up to be Plato's rival. We look back to Aristotle through a great parade of years fourteen times as long as the history of the United States; yet today we can read translations of his writings on ethics, politics, logic, metaphysics, rhetoric, and the natural sciences.

Aristotle's explanation of falling presents a curious blend of observation and preconceived ideas. He had noticed that fire rises, and he felt that the stars must be perfect. Therefore the direction up was good, and fire was good. Conversely, the direction *down* was bad; and the four elements of which he thought our world to be composed — Earth, Water, Air, Fire — differed in virtue in accordance with their behavior when free to fall. Every element had its own level in the world and would go there like a homing pigeon if we let it. A stone or anything else made of earthy

material ranked lowest in the scale of perfection, and its rightful place was as close to the earth as it could get. If we release a stone it will go through fire and air and water to reach its proper level.

This conception of falling made the center of the earth, of course, the worst place in the universe, and saw in the act of falling merely the result of like seeking like. The idea lingers on in our figurative use of the word *fallen* in describing a person. Carrying his idea further, Aristotle concluded, quite logically, that a large massive object, say a stone, must fall faster than a smaller stone. The large stone obviously contained more of the imperfect earthy matter than the smaller one, and if things fall because they are imperfect why shouldn't the worse one fall the faster?

What we are looking for here is the ancient approach to questions that could be settled by experimenting. Aristotle's conception of matter had led him to a very definite conclusion: a heavy stone falls faster than a light one. It was a logical conclusion; it could be tested in a few moments; and the validity of his whole outlook on inanimate nature hung on the outcome. Yet he never tried the experiment, though for several years he had scores of assistants who were paid by Alexander the Great to help Aristotle gather information for his voluminous writings.

Seeing Is Believing

One day a young man in Italy, Galileo Galilei, decided that he did not believe a heavy stone would fall any faster than a light one. He thought to himself, Seeing is Believing. Simple and obvious as that principle may seem now, by voicing it clearly and acting on it Galileo established his position as the founder of experimental science.

The thought of doubting what Aristotle had written was a long time on the way. J. B. Benedetti criticized Aristotle's ideas of motion five years before the date of which we write; but so far as we can tell nobody except possibly Stevinus of Holland, another contemporary of Galileo, had ever subjected Aristotle's ideas about falling bodies to a crucial test until Galileo tried his famous experiment, and Aristotle had been dead for nineteen hundred years when Galileo was fourteen years old.

It seems almost unbelievable to us that in all those centuries nobody should have thought of dropping two stones to see which one struck the ground first. It would have taken just a few moments of anybody's time. Yet the old glories of Greece and Rome had passed away, the dreary centuries of the Dark Ages had run their course. The eight Crusades, though they filled nearly two centuries with blood and excitement, were an almost forgotten incident. Only now were a few brave men beginning to poke their heads up through the clouds of superstition which had smothered mankind for so many centuries.

Columbus had discovered the New World in 1492. Thirty years later one of Magellan's ships, having left its stout-hearted captain dead in the Philippines, cast anchor near Seville, the first ship to sail around the world. In the year 1543 Copernicus had published a book that shattered the beautiful crystalline spheres which an ancient Greek astronomer, Eudoxus, had invented about 370–360 B.C. to carry the moon, the sun, and all the planets and stars in circles around the earth. Copernicus showed that the earth itself, and all the planets go around the sun. Now Galileo was about to discover a world greater than Columbus', because he had the imagination and the courage to say, Seeing is Believing.

What They Said to Galileo

At this time Galileo was a young professor in the University of Pisa, in Italy. Queen Elizabeth was ruling in England. Shakespeare had recently come up to London. Protestants were being slaughtered in Spain, and in England Catholics were being hung, drawn and quartered. Martin Luther, the leader of the German Reformation, had been dead for forty-four years, and Henry the Eighth for forty-three. Printed books had been circulating in Europe for nearly a century and a half. The ancient clepsydra, the water-thief, which marked the passage of time by the slow flow of water through an orifice, was still competing with the newer clocks driven by weights or springs.

When Galileo told his fellow professors what he was going to do they opened their books and showed him what Aristotle had written. "Why go to all the trouble of dropping your weights?" they asked him. "Aristotle tells what will happen. Besides, if you drop them from the leaning tower you will certainly be seen." They went on to caution Galileo against the blasphemy and danger of doubting Aristotle, and added that he might not be as lucky as Copernicus, who, they said, had gotten off easily because he died as soon as his book came out.

Part of what Galileo's colleagues told him was true. But they should not have said that Copernicus was lucky in dying as soon as his book came out. They should have said that Copernicus would not let the printers print his book until he knew he could not live much longer. He knew that the world would not be a safe place for him after those in power had read his book.

Copernicus Refutes Ptolemy

In that book Copernicus showed that the earth and the other planets revolve about the sun. It was the truth, and he knew it was the truth, and though it had been suggested by Aristarchus in the third century B.C. it was now being told more convincingly than at any time since man had walked. But it was not what the Greco-Egyptian astronomer, Claudius Ptolemy, had said in his famous book, the Almagest. For the fourteen hundred years from Ptolemy to Copernicus people had believed that the sun, planets, and stars all revolved around the earth. They believed this because Ptolemy had said so. Besides, they found it pleasant to believe that the earth was the center of all things. It made them feel important. It is hard for us to understand how two men, Aristotle and Ptolemy, could rule men's thoughts about nature for so many centuries.

According to Ptolemy, the earth did not move, and Copernicus knew that to say it did move would bring punishment, perhaps torture and death, down upon him. So for seventeen years he kept his discovery secret from all except those whom he considered his friends. Even so, the word of his beliefs got around, and he suffered persecution. He waited until almost the last minute before giving the manuscript to a publisher. The first printed pages of his great work were put into his hands as he lay dying. He could feel them but he could not see what he had written. Later in the day, he died.

Galileo Tries an Experiment

Hundreds of people are said to have gathered on that day in 1590 to watch young Galileo drop two balls, one heavy, one light,

from the leaning tower of Pisa. He climbed the 180 feet to the top of the tower knowing very well that what he was about to do was revolutionary.

Galileo dropped the balls. They reached the ground at the same instant. They fell side by side all the way. So Aristotle had been wrong all those centuries! Now here was something that had to be explained. Why didn't the heavy ball fall the faster? But many of the spectators merely said it *did*. They were so used to believing what they were told that they would not believe their own eyes.

Bruno Tells the Truth

Now a struggle was on. Galileo and Copernicus *versus* Aristotle and Ptolemy! Aristotle and Ptolemy had been dead a long time, but their followers were very much alive. Copernicus, too, was dead, though not so very long, and he also had a follower. Giordano Bruno had read what Copernicus had written, and he wanted everybody to know the truth. In his enthusiasm he went up and down Italy, telling everybody that the earth did move. He said it was only one of a number of worlds that all moved around the sun, he said the stars were suns like ours, and he said that some of those suns probably had worlds like the earth revolving around them—other worlds that perhaps bore living men, men living and breathing and thinking.

This was too much for the arbiters of opinion. What were men coming to? Galileo was proving that Aristotle was wrong, and Bruno was telling people that the earth was not the only important place in the universe. Bruno was not as great a man as Galileo, so they took action against him first. They burned him to death at the stake in the year 1600 on the Piazza dei Fiori in Rome.

Galileo Looks at the Moon

Galileo went boldly on. He had proved that Aristotle was wrong in saying that a heavy object must fall faster than a light one, but he himself was not sure why objects fall at all. He did not know what weight was. Of course Galileo's discovery showed that falling was no proof of imperfection or inherent evil in matter, for after all Aristotle's prediction was the logical result of his conception of inanimate nature.

Thus Galileo had undermined one superstition, helping to free men's minds from the fear of evils that did not exist, and now he went on to other studies. He never did find out why bodies fall, which is the question we started with at the beginning of this chapter; but he made some splendid discoveries about moons which helped Sir Isaac Newton later to find the answer to our question, so we take a moment to consider moons.

It may seem strange that it was a study of the moon that taught us why objects fall. There are other instances in history like that. In 1868 Lockyer discovered an unknown substance in the sun, which he called helium. Many years later, in 1895, a chemist named Ramsay discovered helium in a rare mineral named cleveite, and later in the same year another chemist, Kayser, found that we had been breathing helium all the time. It was in our own air. Now we extract helium by the ton from the gas wells of Texas, Oklahoma, and Colorado, at a cost of a few cents per cubic foot, and use it to fill our airships, like the ill-fated Macon, to make them float in air.

So Galileo studied moons with a telescope which he had made. It was not the first telescope, but it was the first telescope that was used to make worth-while discoveries. In 1609 he pointed it at our moon and found mountain ranges and broad plains, towering

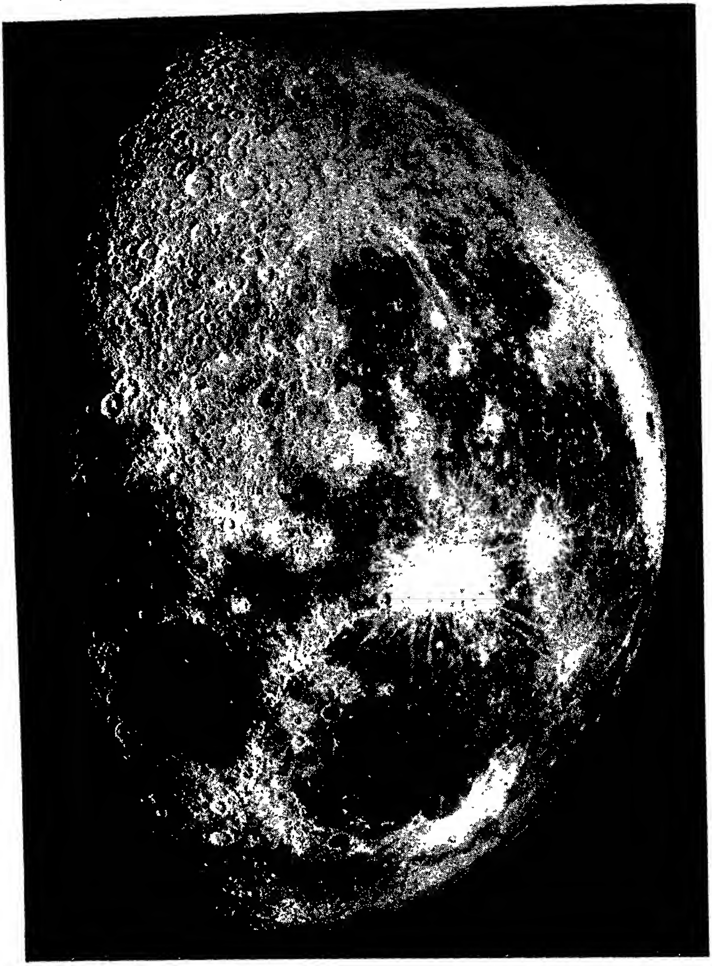


Figure 1. The Moon, nearly five days after the full phase. The crater from which bright rays radiate near the middle of the photograph is Copernicus. The dark area below Copernicus, bounded at the left by mountain ranges, is Mare Imbrium. See the labeled photograph, Fig. 15, for key to lunar features. The sunset line is at the left. (Photographed at Mount Wilson Observatory.)

jagged uplands and deep craters. After twenty-one centuries of uncertainty an idea first advanced by Anaxagoras was proved to be correct. The moon was an earthy object out there in space. There was real ground on its surface. A geography of the moon — we should say, selenography — was possible. Galileo held his breath. It was a beautiful sight, to be sure, and he was the first man in all the ages to see the moon as it really was. We look at the heavens nowadays through telescopes that make Galileo's homemade instrument seem weak and puny, but what he saw through his produced a revolution in the thinking of mankind.

Arguing the Spots off the Moon

Galileo called hundreds of people to look at the moon. Noblemen came, and bishops of the church, college professors and hundreds of others. What many of them said, even some of the professors, sounds strange in modern ears. Their argument ran somewhat as follows:

"Aristotle says that the moon, being a heavenly body, must be perfect. Being perfect, it must be perfectly round, which is the only perfect shape. So, Galileo, the moon cannot have any spots on it. It cannot have these craters, mountains, and dark spots on it. They seem to be there, but that only proves that there are devils in your telescope. This thing which you have made to look through is a thing of evil, and you must be possessed of devils to make a tube that shows things which we know cannot be true. Take care how you cast doubt on Aristotle."

Here, with a vengeance, was a gospel of perfection. Once again men would not believe their own eyes. But let us not feel superior. Nearly a century later, in 1692, nineteen Americans swung in a single year from the gallows in Salem, Massachusetts, executed by their fellow townsmen for fancied commerce with the devil.

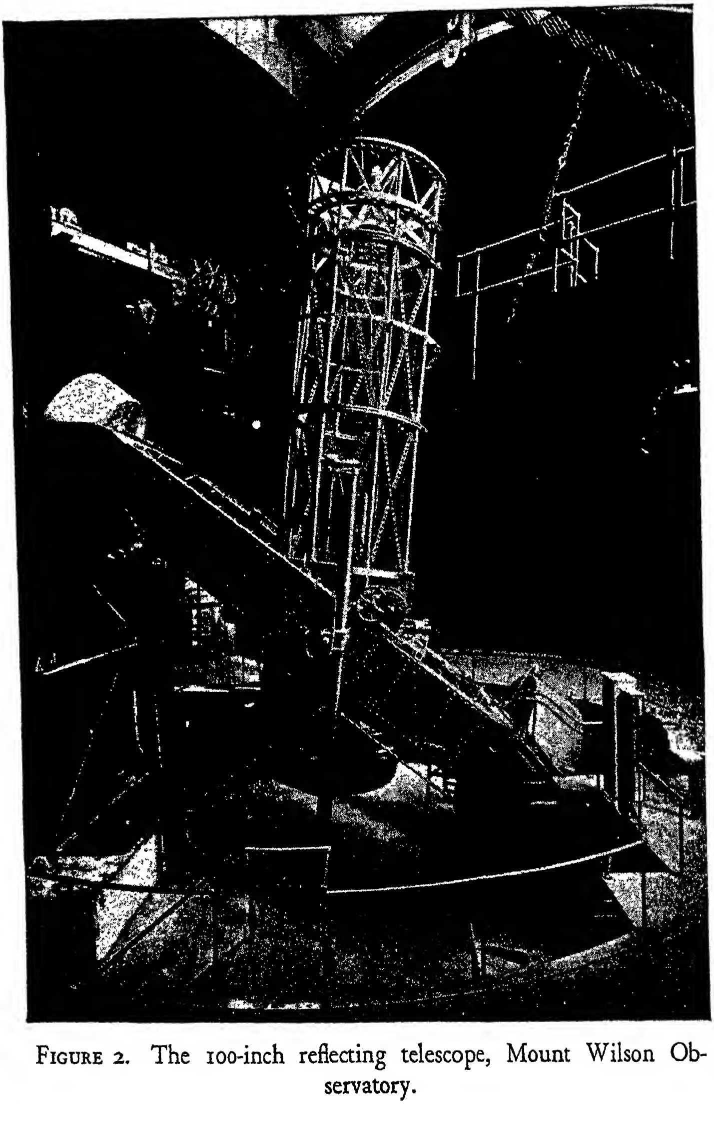


FIGURE 2. The 100-inch reflecting telescope, Mount Wilson Observatory.

Jupiter's Satellites

Galileo went on, conquering a new universe for mankind. He pointed his telescope at the brilliant planet Jupiter, and Lo and Behold! he found four moons revolving around Jupiter as satellites. We have found five more since then, nine in all. A tenth has been announced and awaits confirmation. But Galileo discovered four, and that was quite a plenty for the time. There before him in the heavens he saw happening the same sort of action that Copernicus had described in his book. He saw four moons revolving around Jupiter, exactly as Copernicus had said the earth, Jupiter and the other planets revolved around the sun. It was a solar system in miniature. It was visible proof that what Copernicus had said was at least possible.

Even a small modern telescope, say one with a two-inch lens and a magnifying power of 30 times, will show more clearly than Galileo's showed him, this splendid system of moons. If you look at the moons twice, on different nights, or even twice the same night at an interval of several hours, you will see that the four moons which are visible through small telescopes have changed their positions. You may see one come out from behind Jupiter while you watch, you may see one disappear in Jupiter's shadow. Perhaps two will move past each other while you are looking. These moons of Jupiter move regularly. One thinks of a clock that never needs oiling or winding, a clock set in the heavens, with nine hands each tipped with a moon. We could tell time by them century after century by studying them closely. We look at this celestial clock not face-on, but from the side in approximately the same plane that contains the orbits of the moons, so they seem to be moving back and forth in a line.

Would poets wax more romantic, we wonder, or less, if they

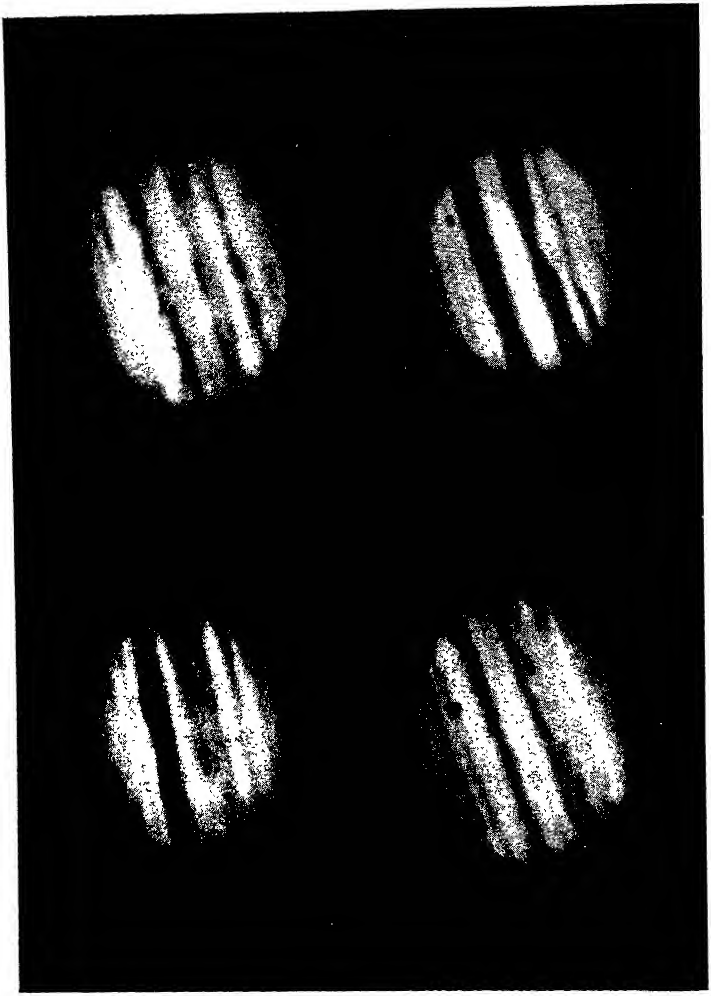


FIGURE 3. The planet Jupiter at different times. Note the cloud bands parallel to the equator, the equatorial bulge, and, on two of the photographs, the shadow cast by one of Jupiter's moons. (Photographed at Mount Wilson Observatory.)

could stroll on this planet that has nine moons, four of them prominent bodies in the sky? Four moons the casual observer on Jupiter would notice especially, the most conspicuous one of the four looking the size of ours, and the least, one-third that large— all moving at different rates, all moving more swiftly through space than ours, and all appearing to move very fast on account of the rapid spinning of Jupiter. One moon might be rising, another setting, at the same time. Another might be high in the heavens, and once in a while all four would be visible, showing different phases. You could have a new moon, a first quarter, and two nearly full. Or perhaps you would prefer four new moons close together in the Western sky shortly after sunset.

So now it was hard to believe that the earth was the center of all things. The earth did not seem to be quite as important a place as Ptolemy had said, and men's minds could expand and dwell on the new glories of the universe. But expansion may be a painful process. The men who ruled Italy wanted everything to be as they had always thought it.

They wanted the planets and the stars to revolve around the earth, they wanted the earth to be fixed and motionless, they wanted the earth to be the center of all things, so that man, who lived there, would surely be the most important object in the universe next to God. If they could not rule the heavens by waving their scepters, they could at least threaten Galileo with torture if he did not keep quiet. They could make him recant, and imprison him, and they finally did.

Galileo spent the last years of his life a prisoner in his own house, a prisoner old, sick, blind, almost friendless. But what a world he gave us before bowing to the authorities! We have merely touched on a few of his triumphs.

Sir Isaac Newton

The year Galileo died there was born in England a child who was to carry knowledge so far beyond anything hitherto conceived that so distinguished a scholar as Lagrange could cast caution to the winds and say of him, "the greatest genius that ever existed, and the most fortunate, for we cannot find more than once a system of the world to establish."

Ancient Greece had given the world a new kind of thinking to take the place of myths. Poland, after many centuries, had given Copernicus. Denmark had given Tycho Brahe. Germany had given Kepler. Italy had given Galileo. Now England gave Isaac Newton, the problem of the planets was to be solved, and, more than that, the edifice of scientific truth was to tower suddenly to splendid heights and command the world's respect.

Never since Isaac Newton has science been seriously threatened in democratic countries. True, some universities banned his teachings for a century. Even today some think that the astronomers who day by day push back the unknown boundaries of the starry universe are making man small and insignificant in comparison, and they rebel, just as the ruling powers rebelled in Italy when it was proved that the earth was not the center of all things. A needless protest! Man is as big as all he knows. Ever since Newton science has gone steadily on, destroying superstition and the fears that it engenders, supplanting rule-of-thumb with exact knowledge, showing us how to fight disease, to see far, to travel fast, to multiply our crops, to alleviate suffering and lengthen life, until today there are vast possibilities only partly realized for bettering our lot.

But we wanted to know why objects fall. Newton came, he found why bodies fall, and in finding out he tied the universe together.

A New Idea: Gravitational Attraction

Newton and the falling apple! Newton's favorite niece, Catherine Barton, who lived with him for many years, told the story to Voltaire. It may be true. Perhaps the apple falling in the garden did suggest the idea of gravitation to Newton. At any rate, he got the idea. This was in 1665, when he was twenty-three years old.

Newton was wondering why bodies fall, he was wondering why the moon goes around the earth, and why all the planets go around the sun. Copernicus had proved that the planets revolve around the sun. Kepler had found the mathematical laws which describe their motion. Galileo had proved that the moon was a real body that *could* go around something, and he had shown that four moons were actually revolving around Jupiter.

It occurred to Newton that perhaps the earth attracts a stone and makes it fall. And if the earth attracts things near its surface, why should it not attract the moon? And why should not the sun, then, attract the earth, and why . . . ? But already we see that he had gotten hold of a bold idea.

Why Falling Bodies Are Accelerated

Newton was already familiar with two kinds of attraction. As early as the sixth century B.C., Thales of Miletus knew of an attraction which we now call electric; and in the eleventh century A.D. the Chinese were using compass needles magnetized with lodestones. In 1600, forty-two years before Newton was born, Queen Elizabeth's physician, William Gilbert, had written the first scientific treatise on magnetism. Newton knew that in suggesting a third kind of attraction, gravitational attraction, he was proposing a new idea which would have to be proved. He recog-

nized, of course, that the objects in a room do not seem to attract each other. Probably every object in a room, persons included, attracted every other object in the room, Newton thought, but the force was so small that they were not drawn together.

But when one of the objects was large the case might be different. The earth has so much stuff in it to attract an object that the latter might come tumbling to the ground. This would explain why things all over the earth fall towards it. The idea would do away with Aristotle's difficulties about down and up once for all.

Such a force would explain why the motion of falling is accelerated. If the earth's pull is able to make objects start falling it is able to make them speed up after they have started. Newton saw that the falling body would gain speed because the same force kept pulling it. If the force merely started the body falling and then ceased to act, the body would move on at an unchanging speed. But apparently gravitational attraction was not a force that one turned on and off. It acted all the time, so that the falling body had to speed up, going faster and faster the longer it fell.

Why Galileo's Heavier Object Fell No Faster

We can imagine that by this time Newton was very much interested in his new idea. He saw that if this new force existed, it would explain the mysterious result of Galileo's experiment with the objects of different weights which he had dropped from the leaning tower. The extra matter in the heavier object would cause the earth to attract it with a greater force, *but that same extra matter would also make the object harder to speed up.* The two effects would exactly counterbalance each other. The situation reminds us of the man whose expenses increased ten dollars every time his pay was raised ten dollars, so he never got ahead.

There is something about genius that enables it to see the basic things which most people overlook and yet which seem to be perfectly obvious once genius has pointed them out. It was nearly two thousand years since Aristotle; it was over three thousand years since the arithmetic and geometry of Ahmôse; it was about six thousand years since Imhotep, the Egyptian physician — and it was an uncertain number of hundreds of thousands of years since man began walking this planet. Not until now had a Newton arisen to explain the behavior of falling bodies by combining force with the concept of *inertia* — the latter a seemingly inescapable fact of our daily experience yet one which had been overlooked as a basic property of matter until Galileo and one or two of his contemporaries began questioning Aristotle a few years before Newton's time.

If you are riding in a speeding automobile and it stops suddenly, your body tends to go forward. If the car stops suddenly enough you go on through the windshield. Why? Your body, like all other matter, has *inertia*. It tends to keep on going. If the automobile is at rest and starts suddenly, your body seems to try to stay behind. If you are sitting on the spare tire and the car starts suddenly enough, it leaves you behind. Why? Your body has *inertia*. It tends not to move if it is not moving.

In short, bodies neither stop, start, speed up, slow down, nor change the direction of their motion of their own accord. All matter has inertia. A force is required to change a body's state of motion or of rest. That is Newton's first law of motion. And if one object contains twice as much matter as another it has twice as much inertia and requires twice as great a force for a given acceleration. The underlying principle here is known as Newton's second law of motion. We have already used it to explain why Galileo's heavier object did not outstrip the lighter. The extra

inertia of the heavier object offsets the extra force, so all falling bodies gain speed at the same rate—provided, of course, they are not so light that they flutter in the air or are otherwise affected by the atmosphere. The coin and the feather falling side by side in a vacuum tube show this very strikingly.

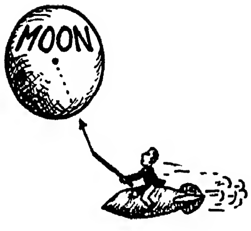
The Moon Is a Falling Body

Turning now to the earth and the moon, Newton decided that even though the two bodies are much farther apart than one of us and the earth, they might still attract each other strongly. Each had a large mass to help in the attracting. He began to think of the moon as a falling body.

One of the most difficult ideas to grasp is that bodies may exist in space with no supports to rest on. What holds them up? One might also ask, Why should they need to be held up? If one pictures a star several millions of millions of miles from anything else in the universe, which direction would *down* be? Why should it fall? Why should it need any support? If it were to fall, in which direction would it start? Why should it start in that direction rather than in some other direction?

Ideas like these kept running through Newton's head. But in the case of the moon, our next-door neighbor in space, the force of attraction which Newton conceived would cause it to fall. The moon is a free untethered body in a vacuum. The slightest unbalanced force would make it fall. A tiny tug plying its trade in the harbor can get an ocean liner moving if it keeps on pushing or pulling. Could the moon fall century after century and yet never collide with the earth? Would there be no need of a super-wharfman to fend it off with his boathook?

Newton thought he saw the answer. He lived a century and a



"DOWN" IS RELATIVE

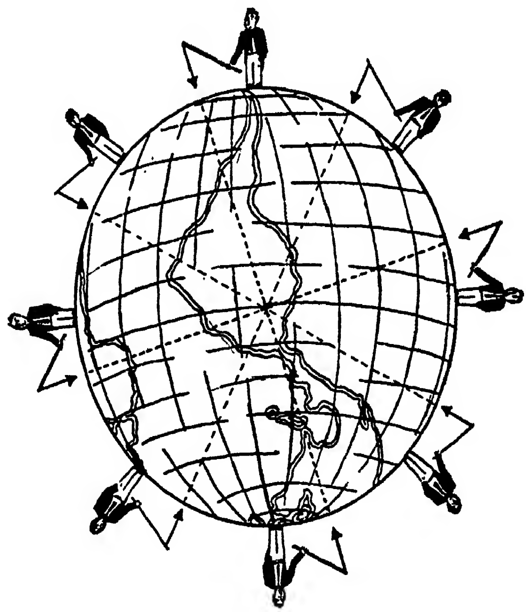


FIGURE 4. Gravitation determines the downward direction.

half too early to enjoy Lewis Carroll's masterpiece, *Alice in Wonderland,* but the answer he gave suggests Alice's experience of having to run as fast as she could to stay in the same place. Newton said the moon could keep on falling towards the earth without getting any closer.

What would happen, he asked himself, if the earth did not attract the moon? The moon would be a casual visitor, flying past us once and then going on in a straight line out into the depths of space, never to return — a beautiful stranger that once passed our way, leaving awe and great stories in its wake. He said if it were not for gravitation we should not have our moon. Objects naturally keep on going in straight lines if they are once set in motion. It takes force to make them move in curved paths, a force pulling towards the center. So he said the moon *is* a falling body, falling just fast enough towards the earth to keep from getting any farther away. If the moon were not a falling body, he reflected, we'd lose it; and if the moon ever lost its speed, it would come smashing into the earth.

Newton Tests Gravitation

But was it all true? The theory seemed so beautiful, it seemed to explain so many mysteries, including the whole Copernican system of planetary motion, that by this time we can imagine Isaac Newton hoping it was true. He set out to test his hypothesis. How he proved it is a long story which we shall not consider in full detail. He expressed his conception of gravitation in a mathematical law which agreed with, and completely explained, Kepler's laws of planetary motion. Then he calculated how the moon would move if his law of gravitation was correct. He reasoned that if, on studying the moon, he should find it moving exactly as his law of gravitation predicted, the law must be true.

Part of the calculation was very simple, but there was one point that was difficult enough to cause Newton a good deal of trouble. The gravitational attraction between two bodies, as he conceived it, depended on the distance between them, and the different parts of the earth were at different distances from the center of the moon. Likewise, the different parts of the moon were at different distances from the center of the earth. This phase of his problem was so difficult that all the mathematics known at that time would not solve it.

Arithmetic, algebra, geometry and trigonometry were not enough. So Newton used a new kind of mathematics of his own invention. He called his new mathematics *fluxions*. We call it the *calculus*. In the two centuries since Newton died, we have been able to solve thousands of problems of great practical importance, hundreds of different kinds of problems, which cannot be solved without the calculus. To select one example from many, the theory and applications of alternating electric currents would still be rudimentary if the calculus had been lacking. No more powerful tool has ever been invented.

A Disappointment

At last Newton's calculations had been completed. He compared his results with the way the moon actually moved. The results did not agree!

The moon did not seem to move exactly as he calculated it would have to move if his law of gravitation were true. He calculated that the moon should fall towards the earth — that is, be deflected from a straight line — a distance of 16.05 feet every minute. However, it appeared by actual observation to fall less than that. It seemed to fall only about 13.20 feet towards the earth every minute. And 16.05 is not 13.20.

We can imagine Newton's disappointment. He was not tempted to announce the result as perfect, and conceal the error. No doubt he could have fooled people easily for a time. Everybody would consider it a tremendous discovery, this law of gravitation which made the universe seem reasonable for the first time. But Isaac Newton laid his great law away. The theory of gravitation seemed beautiful and reasonable to him, he could not find the reason for the error. And who was there to help a Newton?

The Law of Universal Gravitation

But Newton was right all the time. He had had to use the size of the earth in his calculations. At that time it was thought that the earth was less than 7000 miles in diameter. In 1671 a Frenchman named Picard remeasured the earth and found that the size which people had accepted up to that time was wrong by 1190 miles. The earth was actually 1190 miles thicker through the center than had been generally believed.

Newton heard of this new result. Just how soon, we do not know; but at least he heard of it in time to include the law of universal gravitation in his famous book, the *Principia,* the appearance of which in 1687 — twenty-two years after he began his work on gravitation — has been called the greatest event in the history of science.

It is said that when Newton heard of Picard's result he was so excited that, not trusting himself, he called in a friend to make a recalculation according to his directions. The new size of the earth fitted exactly. The number comes out 16.02, which is very close to 16.05. The law of gravitation was proved. The apple and the moon obeyed the same law.

The Nature of an Exact Law

Newton stated his law in universal terms. He was not content to apply it to the falling apple and the earth and moon. He said every object in the universe attracts every other object with a force which is proportional to the product of their masses and inversely proportional to the square of their distance apart.

It is easy to miss the significance of so compact a statement. More than the mere fact of attraction is given. The law illustrates beautifully the sort of thinking that goes on in those sciences which attain the ideal (and the power) of exact and general laws. When, for example, one quantity A is found to be proportional to another quantity B, we know that not only does the first increase when the second increases: they increase in the same ratio. If B is doubled, A automatically doubles. If B is halved, A is halved. But if A were *inversely* proportional to B, it would decrease when B increased, and vice versa. If B doubled, A would automatically be halved.

Thus the law of gravitation can be understood. The force is proportional to the product of the masses. Let two bodies of 10 and 20 tons mass, respectively, be attracting each other. The product of their masses is 200. Replace them with bodies of 5 and 8 tons. The product is 40, which is one-fifth of the original product. Hence they attract each other only one-fifth as strongly as the first pair.

Now suppose we move the original masses farther apart, increasing the distance from 10 feet, say, to 20. The force is inversely proportional to the square of the distance. Ten squared is 100, and twenty squared is 400, or four times greater, so the new force is only one-fourth the former.

Finally, let both changes occur simultaneously. We have seen that the increase of distance reduced the force to a quarter of its

original value; and the substitution of the smaller masses reduced the force to one-fifth. Both changes made simultaneously give the same result as if one change follows the other, so the new force is $\frac{1}{5}$ of $\frac{1}{4}$ of the original value, or one-twentieth.

The scientist avoids all this circumlocution by using symbols. Thus the law of gravitation is expressed as $F = K\frac{M_1M_2}{D^2}$, where F is the force, the M's are the masses, D is their distance from each other, and K is the constant of gravitation, a number which depends on the units used and must be determined once for all by experiment. Seventy-one years after Newton died another Englishman, Lord Cavendish, found K by a very delicate experiment and proved that a pair of metal balls in a laboratory attract each other exactly in accordance with Newton's law.

The attraction was very small. Even two eighty-thousand-ton ships like France's *Normandie* and England's *Queen Mary* would attract each other with a gravitational force of only half an ounce weight when one mile apart. No wonder gravitation went unrecognized for so many centuries!

Note that weight is a force, not amount of matter. If one ship could talk, and were asked how much it weighed, it ought to say: "I weigh 80,000 tons with respect to the earth, and I weigh half an ounce with respect to that other ship over there."

"Weighing" the Earth

When we consider how much harder it would be to lift one of those ships against the earth's attraction than to hold the two of them apart against their attraction for each other, in spite of the fact that the ships are so much closer to each other than to the center of the earth, we are ready to accept a large figure for the amount of material in the earth. Cavendish found that out, too. The mass

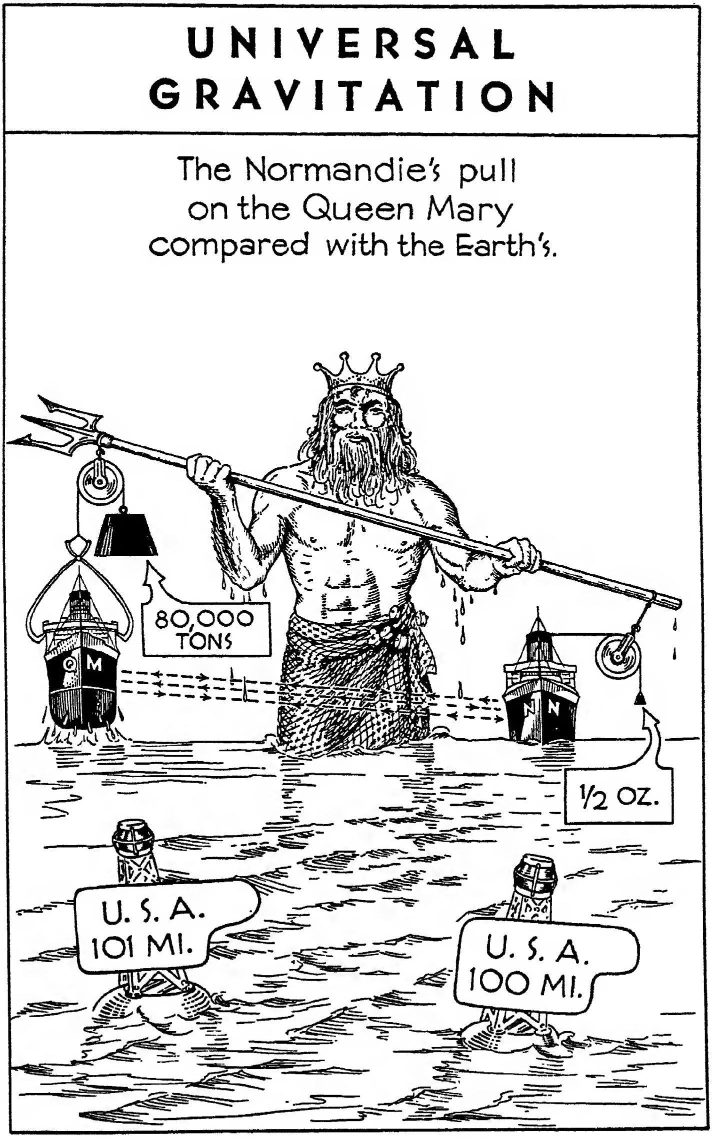


FIGURE 5. The weight of the half-ounce mass hanging over one of Father Neptune's pulleys counterbalances the Queen Mary's attraction for the Normandie.

of the earth is six thousand five hundred and eighty billion billion tons. To avoid cumbersome expressions we use a convenient shorthand for large numbers. The number 1,000,000,000 is written 10^9, because 10 used in a continued multiplication nine times gives 1,000,000,000. Hence a billion billion would be 10^{18}, and the mass of the earth could be written 6580×10^{18}, or 658×10^{19} tons.

Thus Newton's discovery made it possible to " weigh " the earth. Strictly speaking, to weigh the earth would mean to find the force of gravitational attraction exerted on the earth by some other body, say the sun. We should have said that Newton's discovery made it possible to determine the mass of the earth. The masses of the moon, sun and planets could be found by the same principle. Man now knew why things fall, why the moon goes around the earth, and why the earth and the other planets revolve around the sun. Everything attracts everything. One of us, sitting in the room, is attracting every person, every tree, every grain of sand, every cloud, the earth, moon, sun, a mouse in the hold of a ship at sea and every star in the universe. And they all reciprocate.

Fundamental Constants of Nature

The quantity K which appeared in our exact statement of Newton's law of universal gravitation is an example of something so fundamental in the physical universe that it is worth a moment's special attention. We have called it the constant of gravitation. No amount of thinking in a darkened parlor without recourse to experiment — the method so dear to the hearts of the ancients — would ever reveal the magnitude of a constant of nature. If the reader will write that equation on a slip of paper, then let the M's be 1 each (say 1 ton) and the distance 1 mile, he will see that the right-hand side of the equation reduces simply to K, since $(1 \times 1)/1$

equals 1. Thus we see that the constant of gravitation is equal to the force of attraction between two unit masses situated at unit distance from each other. If we use tons and miles as our units, and express the force in pounds-weight, K is found to be .00000000000477, or 4.77×10^{-12}. In the scientific system (grams, centimeters, dynes) K equals 6.66×10^{-8}. But the point we are making is that this constant does not depend *entirely* on our choice of units.

Whatever units we use, K *has* a value — and that value describes something so close to the heart of physical reality that we are at loss for a name. This fundamental property of the universe does not depend on any particular distance, or any particular amount of matter, or on any special kind of matter. It is the same for iron, rock, oxygen, table salt and radium, here or among the stars. There are only a few of these fundamental physical constants, and if we can come to understand what they are trying to tell us about matter and space we shall know precisely what the ultimate nature of physical reality is.

Discovering a New Planet without Seeing It

Often the discovery of a law of nature leads to splendid additions to our knowledge. It is as if an unsuspected signpost suddenly confronted the wanderer in the wilderness, a signpost pointing out a gate beyond which he can find things he did not dream existed. Sometimes after such an experience he goes back home and reveals a new easy way of doing work or perhaps how to talk around the world instead of relaying the news from back-fence to back-fence; sometimes his tales merely make his friends a little less provincial than they were before.

We have already seen that Newton's discovery made it possible

to find the masses of the earth, sun, and planets. It also led to an understanding of the tides; it improved the accuracy with which the positions of planets could be predicted; it explained the movements of comets and thus helped to banish the fear which from time immemorial had seized mankind whenever one of those strange visitors hove into view. And in one dramatic moment it revealed a new planet before it was seen.

The five brightest planets cannot properly be said to have been discovered. Copernicus, in effect, added a sixth; since he showed that the earth was a planet, its orbit lying between those of Venus and Mars. In 1781 William Herschel, the English music-master and self-taught astronomer, discovered a seventh, Uranus, more remote from the sun than any hitherto known. With a homemade telescope (but the most powerful then in existence) Herschel was painstakingly sweeping the heavens when he saw an object that showed size, a disk, and therefore could not be a star. Subsequent study showed that it moved against the background of stars and was, indeed, a planet.

With the aid of the law of gravitation the path which Uranus would travel was confidently calculated before it had traversed more than a small fraction of its 84-year round trip from the point of discovery; but Uranus gradually drew away from the path marked out for it. By 1844 the deviation had grown as large as one-sixteenth of the moon's apparent diameter, an amount which even after the perturbations due to the attractions of all known planets had been allowed for left what was rightly termed an intolerable error.

A law, like man, is known by works. Was the law of gravitation rigorously true? Had some error crept into the structure of reason which Newton had erected? Urbain Jean Joseph Leverrier believed in reason, he had confidence in the uniformity of nature and faith in himself. Also, he had genius. Laboriously but surely

Leverrier calculated *where some hitherto unknown planet must be* to produce, by its gravitational attraction, Uranus' apparent violation of the law. Then he wrote to a young astronomer who had a telescope: "Direct your telescope to a point on the ecliptic in the constellation of Aquarius, in the longitude 326 degrees, and you will find within a degree of that place a new planet, looking like a star of about the ninth magnitude, and having a perceptible disk."

Johann Galle read the note in Berlin and waited impatiently for night to come. Sir George Airy, Astronomer Royal of England, had a somewhat similar note from John C. Adams, who also, quite independently, had solved the problem. But Airy delayed, perhaps because Adams seemed lacking in confidence. Galle pointed his telescope where Leverrier had directed, and another planet was added to our map of the heavens. Out there near the frontier of the solar system Galle saw with his eye the new world which Leverrier had already seen with his mind.

How Newton would have enjoyed that moment! But this was 1846, and the man who had found the law that enabled Leverrier to locate Neptune had been dead for more than a century. Newton died at the age of eighty-five, after making many discoveries not touched on here — a man honored throughout the world, not persecuted for finding truth and destroying ignorance — and he was buried in Westminster Abbey.

The Latin inscription on the tablet above his tomb, translated, says: "Mortals, congratulate yourselves that so great a man has lived for the honor of the human race."

Newton himself said, modestly: "If I have seen farther than other men, it is because I have stood on the shoulders of giants."

Let us leave Newton resting in Westminster, while we go on to see how gravitation affects our lives. It would be an extraordinary world indeed if there were no attraction to give things weight.

Chapter 3

SOME CONSEQUENCES OF GRAVITATION

Gravitation affects us, directly or indirectly, in so many ways that it is hard to decide where to start in describing its influence. First of all, of course, we must come to view the earth as an astronomical body, to see it as a whole. The earth is a ball of medium size, as planets go. We know it is spinning rapidly; we notice the mud being thrown from a spinning automobile wheel; yet we never hear of anybody leaving the earth bodily and going off into space. Above us there is nothing but a thin layer of air, then great stretches of open space in all directions.

Comparing the Earth, Sun and Moon

A good way to form a mental picture of the earth as a whole is to compare it with the two principal objects in our sky. The moon's mean (average) distance from the center of the earth is 238,857 miles. A driver travels that far while wearing out three automobiles, at eighty thousand miles per car. Going around the equator ten times builds up a mileage which, if straightened out, would carry one well beyond the moon. Whether we call that distance large, or small, depends on our point of view. The moon is 2160 miles in diameter, a little more than a fourth as thick through the center as the earth. It looks like a fairly small disk in the sky, so we judge that it must be rather far to appear as small as it does. Yet it is near as compared with the sun, whose mean distance is 92,897,000 miles. If we were as close to the sun as we are to the

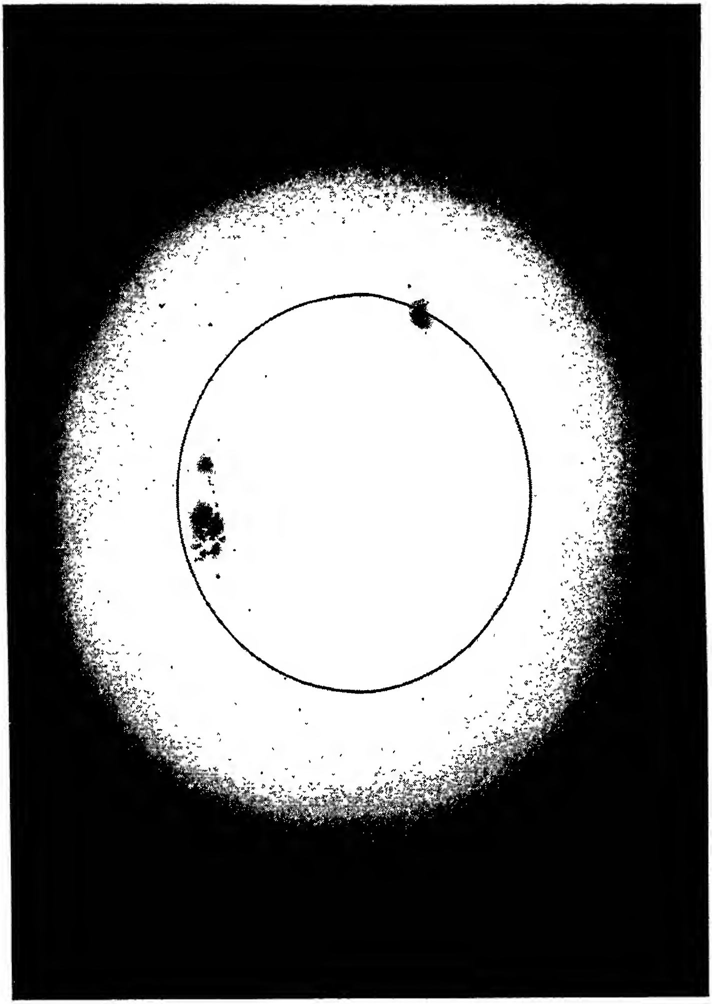


FIGURE 6. Moon's orbit drawn on photograph of Sun. Note also the sunspots, including one of the largest groups ever photographed. The black pointers at edges are instrumental. (Photographed at Mount Wilson Observatory.)

moon, white-hot eruptive prominences leaping from the sun's surface would lick our faces.

The sun is 389 times as far from the earth as the moon. At that distance a body the size of the moon would appear no larger than a dime half a mile away. The apparent size of a body depends, of course, both on how large it actually is and on its distance from the observer. The sun appears to be nearly the same size as the moon; that is, it covers about the same fraction of the sky. If its apparent size were precisely the same as the moon's, we should conclude that it must be 389 times as thick as the moon through the center in order to look that large although 389 times as far. Actually, the sun's apparent diameter is slightly (3%) greater than the moon's, which gives it a real diameter 400 times the moon's. We must picture it as being 400 times as wide as the moon from left to right, 400 times as tall from bottom to top, and 400 times as thick from front to back. Multiplying those three 400's together, we find that it fills sixty-four million times as much space as the moon does.

Suppose the sun were hollow. We could get 64,000,000 moons in it if we squashed them to fill up all the space solidly. Or, if we placed the earth at the center, with the moon going around it at its present distance, the moon would be only slightly more than halfway out to the surface of the sun. And there are enough tons of matter in the sun to make 332,000 earths.

Yet the nearest star, Alpha Centauri, is so far away that from it the keenest observer would see the sun as a mere point of light. He would see it as a star, which is what it really is. If he looked through a telescope as good as our best, even one as powerful as the new giant now being built, the sun would still look to him like a point of light. And he would never know that the earth existed, or any of the other planets, not even Jupiter.

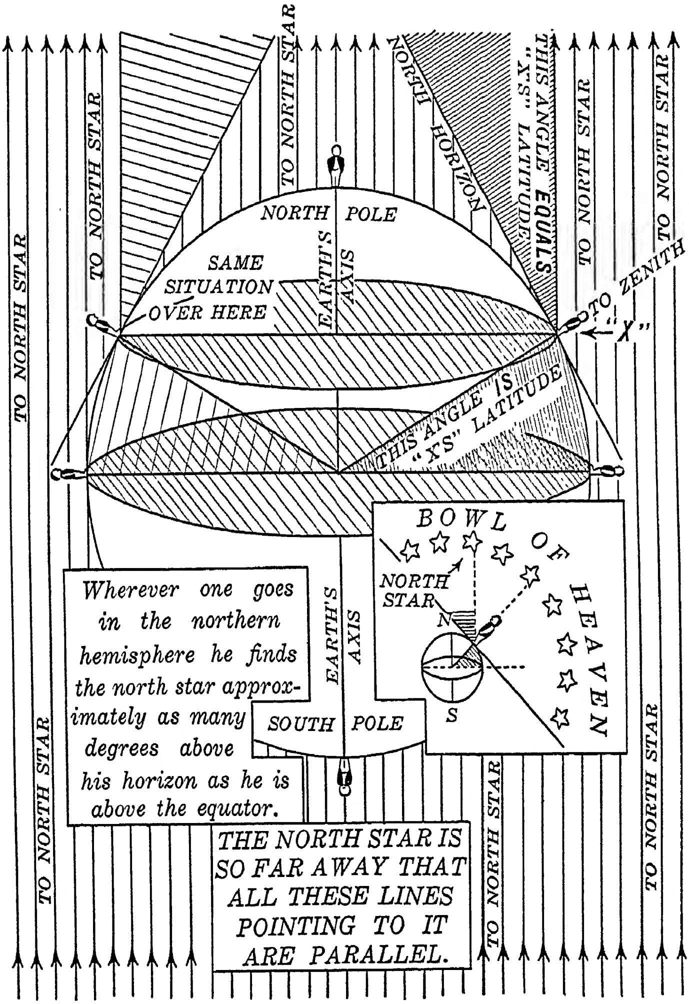


FIGURE 7. Where to Look for Polaris.

The Earth's Rotation

Here in our solar system under the stars the planets are not only revolving around the sun: they are rotating on their axes, as well. The earth's axis always points very nearly to the North Star, Polaris. Two objects covering as much of the sky as the moon does could be driven shoulder-to-shoulder between Polaris and the true pole of the heavens; but for the casual observer Polaris is close enough to the celestial pole to seem to stand still while all the other stars appear to go around it in circles as a result of the earth's spinning.

At the north pole one would find Polaris overhead, in the zenith; and the other stars would appear to circle around it parallel to the horizon, never rising or setting. Traveling southward, one would notice Polaris getting lower, until at the equator it would be on the horizon. Wherever the observer, the angle between Polaris and the horizon is the same as the latitude. At New York, or Denver, or Indianapolis, or any other place where the latitude is about forty degrees north, the North Star is about forty degrees above the horizon, day and night. At Buenos Aires it is always about 35 degrees below the horizon.

If we count turns by the stars we find the earth's true rate of rotation, one turn in 23 hours 56 minutes. For practical reasons we use equalized suntime and so take 24 hours to be a day; but of course the sun's apparent motion is due not only to the earth's turning but to its annual orbital motion as well. Hence the earth completes an extra fraction of a turn in one 24-hour day. Counting turns by the sun would be like tallying laps around a running track by successive crossings of a slowly advancing finish line. So a star rises four minutes earlier every night, two hours earlier every month, and gradually the whole panorama of the heavens

goes through the night sky, all because of that four-minute difference between the earth's true rate of spin and the mean solar day.

Around the equator is 24,902 miles; to be carried that distance in 23 hours 56 minutes means that the equatorial dweller is traveling

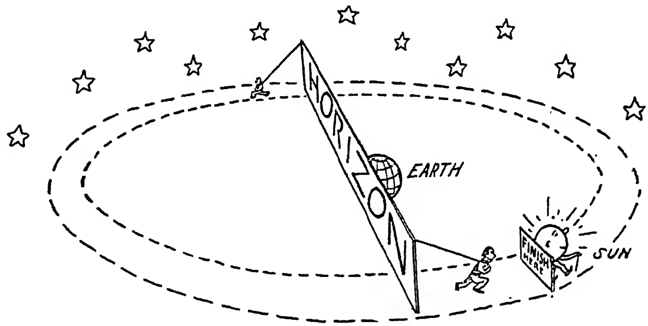


FIGURE 8. Why stars rise four minutes earlier every night. The earth's motion in its orbit gives the sun an *apparent* motion, and the earth must complete slightly more than one rotation in order to bring the sun again above the horizon. A star which rises due east at 8:00 P.M. October 1 will rise about 6:00 P.M. November 1.

in a circle at the rate of 1041 miles per hour. Should one not expect centrifugal effects when whirling at that rate? At either side of the equator a point on the surface describes a smaller circle and so is not traveling quite so fast. At Tallahassee the surface speed is 893 miles per hour; at New York 800; at Nome, Alaska 456; and at the tip of the north pole zero miles per hour. We become vividly aware of this motion when we watch the earth's horizon cross the glowing disk of the sun at sunrise or sunset, or when we focus a telescope on the celestial scenery and watch it go past.

Imagining ourselves out in space far enough to view the earth as a whole we look back and see an almost perfect sphere spinning with its axis always pointing to the North Star and at the same time traveling through space around the sun, carrying the moon

with it. The centrifugal bulge at the equator, and the resulting flattening of the polar regions, produce a difference of only 26.7 miles between the longest and shortest diameters of the earth (7900.0 against 7926.7). From our imagined point of vantage the

FIGURE 9. Evidence of the earth's rotation. A telescope left focused on Polaris for one hour yielded this photograph of star trails. Polaris' trail is the bright one slightly below the true pole of the heavens. (Photographed at Yerkes Observatory.)

earth would look no rougher, relatively, than a bowling ball, the highest peaks amounting to no more than roughnesses 0.005 inch deep on a seven-inch ball.

Centrifugal Force

The same gravitational force that makes things fall is what enables us to remain without effort on the surface of the whirling earth as we take our brief ride through space and time. Objects do not move in circles of their own accord. When an iron bolt

is whirled around on the end of a string, the force that keeps the string stretched taut is called the centrifugal force. The object seems to pull away from the center, and we call that tendency the "center-fleeing" or centifugal force; but this is merely the object's reaction to the center-seeking or centripetal force which must be applied to the string. Newton's third law of motion states that to every action there is an equal and opposite reaction—a truth which doubtless sounds reasonable to anyone who has felt the recoil of a heavy-gauge gun. How could one avoid falling if the floor did not exert an upward reaction equal to his weight?

The centrifugal force is real so long as the pull towards the center exists, and we get into no difficulties by using it provided we never forget that it ceases to exist the moment the center-seeking force ceases to act. Thus, if the string breaks, the object does not fly outwards, but is now a moving body freed from restraint and by Newton's first law of motion tends to travel on in a straight line in the direction in which it was moving at the instant the string broke. One can readily prove this by letting the string pass through an intense flame, to cut it.

Posters advertising automobile races often show the outside wheels leaving the ground on a curve, probably because the artists have noticed the shape of a speed bowl or watched bicyclists leaning to the inside when rounding a curve. They forget that curves are banked on the outside to prevent overturning in that direction. The bicyclist leans to the inside for the same reason. Cream separators of the rotating type operate by the principle of centrifugal force, the heavier milk seeking the outside and forcing the lighter cream towards the center. Centrifugal governors for steam engines are common, also centrifugal switches to change connections automatically when electric motors have come up to running speed.

Automobiles equipped with tires whose outside diameter is about 28½ inches (a widely used size) need to travel only a fraction over four miles an hour to make the centrifugal force on a tire tread as great as its weight, pound for pound. And if the car travels 45 miles per hour, every particle of matter in or on the tread is subjected to a force 114 times its own weight. No wonder the mud flies off — or any insects that might try to cling in the crevices. Picturing insects being flung off that artificial planet reminds us what can happen when the rotation is sufficiently rapid. Yet we saw that the equatorial belt of the earth is rotating at 1041 miles per hour — 23 times the speed of the 45-mile-per-hour tire tread. Perhaps we had better look into the law of centrifugal force.

The centrifugal force is directly proportional to the square of the speed and inversely proportional to the radius of the circle. Squaring the 23 of the preceding paragraph we get 529. Thus, if the speed alone mattered, the force on a person living near the equator, say at Quito, Ecuador, would be about 529 times 114, or approximately sixty thousand times his own weight, and Quito would go off into space. But the equatorial radius is, in round numbers, 18,000,000 times the radius of the tire tread, and this of itself reduces the force eighteen-millionfold. Taking both factors into account we see that the centrifugal force on an equatorial object is about one eighteen-millionth of 60,000 times its weight, which is 1/300, or half a pound on a 150-pound man. Avoiding round numbers one gets 1/289 instead of 1/300. Thus only a fraction of our true weight is needed to keep us from being thrown off, and the remainder of the earth's gravitational pull on us makes it safe to move around.

Suppose the Earth Rotated Faster

If the earth should spin seventeen times as fast as it now does, we should have trouble staying on our planet. At that rate of rotation — which would give us a day only 1 hour 25 minutes long

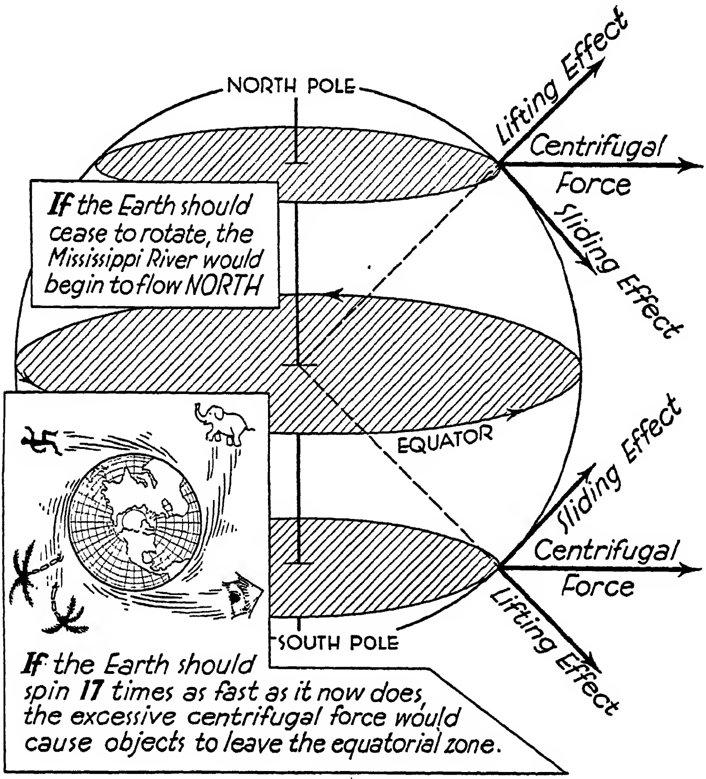


FIGURE 10.

— the centrifugal force on a body at the equator would be equal to its weight. There would be no use holding on to the trees; for they, too, would be on the verge of leaving. Any further increase

of the earth's rotational speed would cause the trees, rocks, oceans, and every loose thing to be flung off, and the earth would bulge so much more than at present that it might possibly break up.

We do not know of any planets that spin as violently as we have pictured. Jupiter, the largest, spins the fastest. There the day averages less than ten hours from one sunrise to the next. If the earth's surface speed were as great as that at Jupiter's equator, our 150-pound man at Quito would seem to weigh only 115 pounds. The other 35 pounds of his true weight would be neutralized by centrifugal force. Through the telescope one can notice two effects of Jupiter's rapid rotation. It is distinctly bulged, much more so than the earth; and clouds are always to be seen arranged in conspicuous belts parallel to the equator, showing the direction of spin.

When a Spinning Body Shrinks

Centrifugal force has been suggested as a possible cause to account for some of the double stars which abound in the heavens. A star, cooling and contracting, is supposed to have come to rotate so fast that it divided into two. A simple experiment suggests how the gain of speed might be produced. Get a small object to whirling around on the end of a string, then let the string wind up on the finger. As the string shortens, the whirling object completes more turns per second and the centrifugal force increases. In this case there is no gain of energy, since the stationary finger used as a pivot is not doing any work; but it is easy to see that if the whirling mass did not negotiate more of the smaller circles in a given time some of its energy of motion would have disappeared without compensation, thereby violating a fundamental principle of nature, the law of conservation of energy.

The effect can be shown to better advantage with one's own body. If, while seated on a rotating turntable, you extend your arms suddenly with a heavy object in each hand, you notice instantly a retardation, as if invisible but powerful brakes had been applied; and on bringing the masses close to your body again, simulating the contraction of a star, you find yourself rotating faster. The results are more striking than in the case of the string winding up on the finger; for here you do work in pulling the weights towards your body against centrifugal force and so increase the energy of rotation at the expense of energy gained from food previously eaten. The principle of conservation of momentum, not energy, would now be needed for a complete explanation. We shall hear more of conservation later on.

If a star cools it will contract; and if already rotating it will spin faster, gaining rotational energy as a result of the work done by gravitational attraction in pulling the star-matter closer to the center. So long as shrinking continues, the rotational speed will increase; until finally the centrifugal force may become so great that the star breaks in two. It is not yet certain whether a centrifugal break-up of this character would account for certain characteristics of the double stars; but the hypothesis seems more promising, at present, than the alternative, which assumes that one member of a binary star has captured its mate by gravitational attraction.

At one time it was widely believed that a similar action had caused the solar system to be formed. This was Laplace's famous nebular hypothesis. All the matter now forming the solar system was supposed to have been contained in one great gaseous nebula extending beyond the orbit of the outermost planet, and slowly rotating. As the rotating nebula radiated and cooled it contracted and rotated faster, until parts were flung off and left behind at

different distances to form the planets, including the earth. This theory, proving untenable, has been supplanted by one which, as we shall see, uses gravitational action to explain the birth of the planets in a way that agrees with their observed characteristics.

Gravitation Holds the Atmosphere

Gravitation does more than enable bodies to remain on the surface of the earth. Twenty thousand times a day, more or less, we breathe. Twenty thousand times a day, if we had to give thanks for every breath, we should owe a vote to gravitation, which keeps the most important of all our natural resources with us. Some countries have no iron, some no coal, some no oil. Canada has almost all the nickel. European countries use hydrogen, a dangerously inflammable gas, to fill their dirigible airships; but we use the safer gas, helium, because we have found it in quantities in natural gas wells. Turning from countries to larger units, we must recognize that air is one of the natural resources which a heavenly body may, or may not, possess. Our neighbor the moon, so like the earth in many respects, has no atmosphere.

We know this because our telescopes never show any twilight on the moon. As additional proof we find its edge always perfectly sharp and clean-cut when silhouètted against the sun at the time of a solar eclipse. We see also that its surface is always clear: no clouds, no fog or haze to blur its landscape. And when the moon passes between us and a star, occulting it, as we say, the star disappears instantaneously, not gradually as it would if the moon were pushing an atmosphere out as an advance guard between us and the star before it got its solid body in the way. No telescope is needed to make this interesting observation. The star disappears with startling suddenness. The week following new moon

is the best time for the test: for then the star disappears before the sunlit part of the moon reaches it. One finds the dark edge of the moon without seeing it.

The proof is certain that the moon has no atmosphere, unless indeed an undetected one-thousandth of one per cent of our own quantity, by pressure measure, be claimed; yet in all probability, both the moon and the earth were once part of the sun, formed at the same time, of similar materials. Doubtless the moon started its celestial career with a blanket of air. Even if that was not the case it would have gained an atmosphere of gases by evaporation, by the action of volcanoes, and by the effects of meteors, the so-called shooting stars, which struck it, and still strike it, daily, in enormous numbers. Yet it lost that atmosphere molecule by molecule. One after another they escaped into space, until finally the solid surface of the moon was left in contact with a vacuum, empty space, sheer nothingness.

Imagine the mounting terror of a race which should find its air getting thinner year after year. Imagine the grim warnings of scientists, the indifference of early generations, then the public gatherings, the conferences of experts, the lobbies, the loud demands that the administration take steps to ward off the impending doom. Would an attempt be made to roof over large areas, or to supply air as a public utility? Would the last hardy remnants of a vanishing population retire into caves? It would be a losing fight in any case. Even with an artificial supply of air for breathing purposes, surface conditions without an atmosphere would be unbearable.

But let us not waste our sympathies. It is not at all likely that there were any witnesses to take note of what would otherwise have been one of the great catastrophes of all times. Let us rather consider what an atmosphere is, how it affects us, why it must be

held, and why the earth, though so close to the moon and only four times as large in diameter, can hold an atmosphere while its neighbor cannot.

Pressure of the Atmosphere

We walk around on the bottom of an ocean of air. Pressing down on every square foot at the level of the sea is a little more than one ton of air. If you will estimate the number of square feet of surface which your body exposes to the air, you will know with how many tons of force the atmosphere presses against you. If it were not for the pores and openings which permit equalization of pressure, our bodies would collapse like eggshells. When air is withdrawn from the straw at the soda fountain, the weight of the air pressing down on the exposed surface of the liquid is what pushes the beverage up the straw. Strictly speaking, there is no such action as suction, which implies a pull.

The atmosphere presses down on the earth with a weight equal to that of an ocean of water completely covering the earth to a depth of 34 feet. That is the reason why a pump that depends entirely on atmospheric pressure cannot lift water higher than 34 feet. An ocean of mercury (quicksilver) thirty inches deep all over the earth would have the same weight as the atmosphere. When we use a barometer, watching for signs of a storm, we are merely balancing the weight of a column of mercury against the weight of a column of air of equal cross section and extending to the top of the atmosphere. If the mercury column is shorter than usual, we know that air currents have lightened the atmosphere above our locality and that air from regions of greater pressure will soon be rushing in, bringing winds and a change of weather.

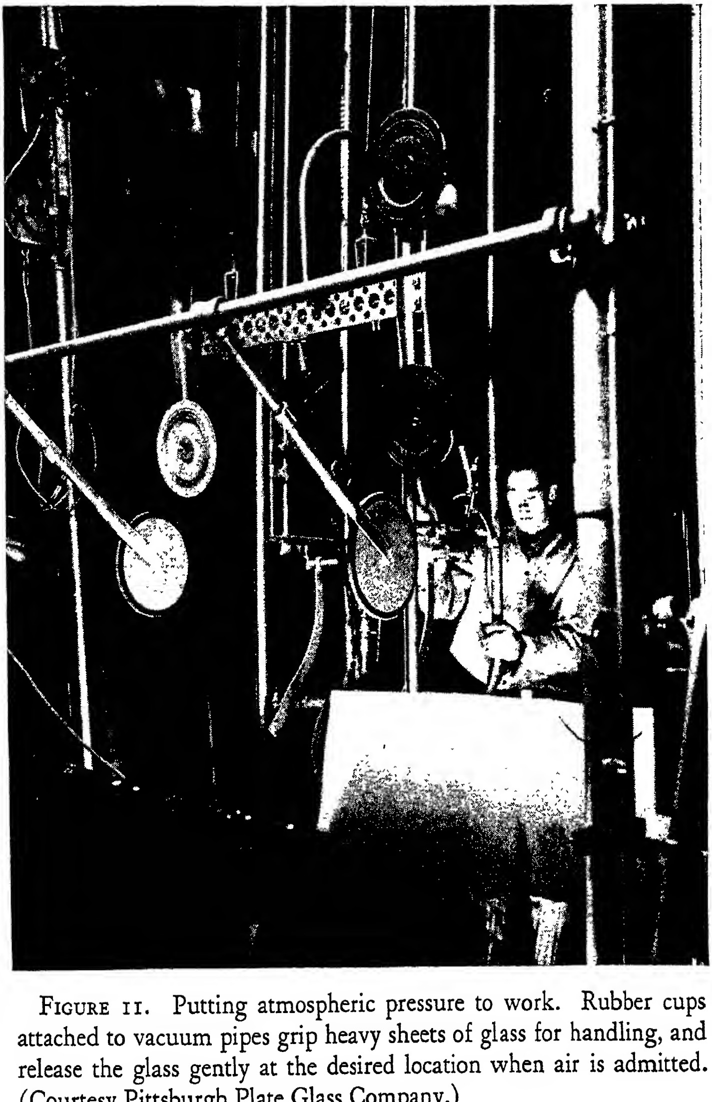


FIGURE 11. Putting atmospheric pressure to work. Rubber cups attached to vacuum pipes grip heavy sheets of glass for handling, and release the glass gently at the desired location when air is admitted. (Courtesy Pittsburgh Plate Glass Company.)

Composition of the Atmosphere

The lower layers of the atmosphere consist largely of nitrogen and oxygen. There is approximately four times as much nitrogen as oxygen, and these two gases comprise all but about one-fiftieth of the lower atmosphere. The small remainder is composed of many gases, including carbon dioxide, water vapor, neon, helium, argon; krypton, xenon, ozone and hydrogen.

The oxygen, of course, supplies our lungs. It combines with many elements, producing slow oxidation in some cases, rapid combustion in others. If red-hot iron is placed in pure oxygen, its rusting is so accelerated that it burns with a white dazzling light. The activity of oxygen is such that it would disappear in the course of time if the supply were not replenished.

Fortunately, plant and animal life complement each other, in a sense. Both require atmospheric oxygen, it is true, and both return carbon dioxide to the air, the human adult exhaling as much as two to two and a half pounds of carbon dioxide in twenty-four hours; but whereas to man carbon dioxide is a waste product that must be gotten rid of on pain of convulsions or death, plants are able to utilize it in such a manner as to restore oxygen to the atmosphere. In forming glucose (grape sugar), for example, the plant uses carbon dioxide taken from the atmosphere and water absorbed, with few exceptions, through the roots. A molecule of carbon dioxide contains one atom of carbon and two of oxygen; a molecule of water contains two atoms of hydrogen and one of oxygen. Six molecules of each, then, not only furnish the total of six carbon atoms, twelve hydrogen, and six oxygen needed to form one of the highly complex glucose molecules, but leave a remainder of twelve oxygen atoms which are returned to the air as six molecules of free oxygen. This satisfactory replenishment of the

atmosphere's oxygen content (not to mention the usefulness of the glucose as a food and plant-builder) is dependent on intermediate actions which are not understood, though known to involve sunlight and chlorophyll.

Carbon dioxide is less abundant in the atmosphere than the rare gas argon; yet that small fraction of one per cent of the atmosphere is the source of the most characteristic constituent of organic matter, carbon. Parenthetically, we see in the presence of this minute percentage of carbon dioxide one of the many conditions which must be satisfied if life is to be possible on a planet. The distance from the sun, which determines both the average temperature and the length of the seasons; the inclination of the planet's axis to the plane of its orbit, an angle on whose value the severity of the seasonal changes depends; the rate of rotation on that axis, which controls the length of the day and hence the difference between day and night temperatures; the size and mass of the planet, which together, as we shall see, determine both the possibility of an atmosphere and its density if one exists; the composition of the atmosphere—on these and other factors life hangs precariously.

The nitrogen in the atmosphere dilutes the oxygen and thus makes a mixture suitable for breathing. When combined with certain other elements it yields fertilizers and explosives. Nitrogen and oxygen, despite the great activity of the latter, can remain mixed together indefinitely as separate elements. Lightning, by discharging electricity through the mixture, causes them to combine in limited quantities; and certain bacteria, working either in the soil or in the roots of plants, notably legumes, promote the formation of useful compounds containing nitrogen originally occluded from the atmosphere. Modern chemistry has developed artificial methods. If Germany had not discovered how to fix

nitrogen, the war of 1914–18 could not have lasted four years. Germany was shut off by sea, unable to import the nitrates found deposited in Chile; but she manufactured what she needed for war explosives out of the air. When we speak of making something out of thin air, we are not necessarily referring to illusions. Millions have been fed with food containing what was once atmospheric nitrogen, and many have been slaughtered with munitions partly made out of air.

The gas which emits the intense red light in the electric tubes of advertising signs is neon. The water vapor yields clouds, rain, and all that flows therefrom. Argon or nitrogen within the bulbs of incandescent lamps retards the evaporation of the white-hot filament and thus permits the lamp to be operated at the high temperature needed for efficient production of light. Air could not be used because the oxygen would burn up the hot filament.

Weight on the Moon

We see the importance of an atmosphere even before we touch on climate, temperature, erosion, and surface conditions in general. What causes have operated to favor the earth with a permanent atmosphere while one is withheld from the moon? The student of science will not seek an answer in cosmic partiality or in the play of chance in the universe. We seek an explanation in the two bodies themselves, and in doing so come upon some significant information about the nature of gases.

The moon's gravitational grip on objects at its surface is easy to calculate. The earth contains 81.56 times as great a mass as the moon. If the two bodies were of the same diameter, this would cause objects to weigh 81.56 times as much here as on the moon. But the moon, by virtue of its smaller size, permits objects to be

3.66 times as close to the center as is possible on earth, and this reduces the disparity. Remembering that the square of the distance is involved, we find that the lunar object weighs one-sixth as much as it would on earth.

Thus large masses could be lifted with ease. A 200-pound man would weigh no more than a 33-pound child does here; missles would rise to great heights; ordinary walking would proceed by a series of kangaroo-leaps; and at a ball game played by athletes as strong as ours the prodigious hits, runs, jumps and throws would present a spectacle whose weirdness would be accentuated by the uncanny effect of slow motion as one watched objects falling leisurely back to the ground. For a given initial velocity, projectiles or high jumpers would remain above ground six times as long as here and go six times as far; but since in the take-off the projective force must overcome both inertia and weight, the former the same everywhere but the latter so small on the moon, it seems that the initial velocity would also be greater, so that the duration and distance of flight would be increased more than sixfold. To fall from a given height, bodies would require about two and a half (the square root of six) times as long as we expect on earth: one would have time to change his mind after dropping something and pick it out of space. Rope swings would oscillate two and a half times as slowly, and pendulum clocks would run correspondingly slow. The observer seeking a possible explanation of the immense sizes of the craters on the moon should bear in mind that displacements of matter by volcanic action of a given violence, or by the impacts of meteorites, would occur there on six times as large a scale as here, and that, once formed, craters would remain sharp and distinct, there being no atmosphere, with all that an atmosphere entails, to obliterate them by erosion.

The Moons of Mars

Lest anyone think that our conditions are standard, and the moon a queer exception, let us take one glance at the two satellites of Mars before we go on with the matter of atmospheres. Deimos, the smaller of Mars' two moons, is about five miles in diameter.

FIGURE 12. The earthlit moon. The earth is nearly full to the moon when the moon is crescent to us. Sunlight reflected from the earth faintly illuminates the dark part of the moon. (Photographed by Barnard at Yerkes Observatory.)

To us it appears no larger than a silver half dollar would look 130 miles away if we could clear away the air to see it; yet this small object, hardly larger than one of our mountains, walks its beat around Mars with as sure a tread as any cock of the heavenly walk. On Deimos our 200-pound man would weigh about an ounce and a half. If he started a stone upwards as fast as one does here to make it rise six feet it would escape forever; while throwing it directly forward from the highest point at a certain smaller speed could result, if the satellite is round, in striking oneself on the back of the head — a round-the-world boomerang. Garbage disposal

would present no difficulties: one would litter up the heavens if he tossed an orange peel.

And Deimos revolves so nearly in step with Mars' rotation that 66 hours elapse between its rising and setting: it changes all its phases twice-over without retiring decently below the horizon.

Phobos, the other satellite, is about ten miles in diameter, but so close to Mars that to an imaginary Martian it would appear one-third as large across the center as our moon looks to us.* It whips around Mars so fast that it makes itself rise and set. It rises in the west, sets in the east, and with this curious backward motion goes through all its phases, from new to full to new again, in eleven hours, less than one average night on Mars.

The Moon's Rotation and Revolution

Returning to the retention of atmospheres, we have seen that gravitational attraction at the moon's surface, though small, is ample to overcome a centrifugal force many times as great as that which objects at the earth's surface experience as a result of the earth's rotation. Can it be that centrifugal force on the moon is still greater, so great that the atmosphere has been thrown off? Before drawing any conclusions let us quickly examine the evidence.

The moon rotates once on its axis in 27.32 days. This coincides with the period in which it revolves around the earth. Thus the moon always presents the same face to view: Galileo saw the same side that we see now. Of course we know that a somewhat longer period (mean: 29.53 days) intervenes between one new moon and the next; but that is because the moon must complete more than one full revolution around the earth in order to pass through all its phases. When the moon is approximately between the earth and the sun its sunlit half faces away from the earth; when it has moved

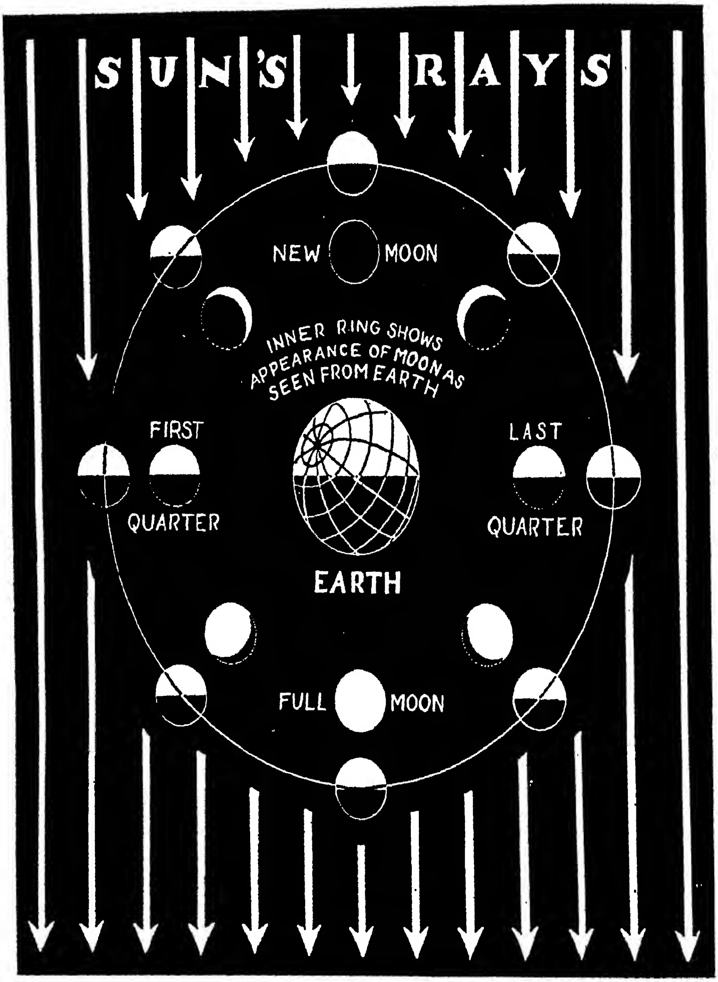


FIGURE 13. Except at times of eclipses, half of the moon is always bright, but we see different fractions of its daylight half as it revolves around the earth.

around to a point opposite the sun its entire sunlit half faces the earth. One looks towards the sun to see a new moon, away from the sun to see a full moon. Thus the full moon rises at about the time the sun sets and remains visible all night; whereas when

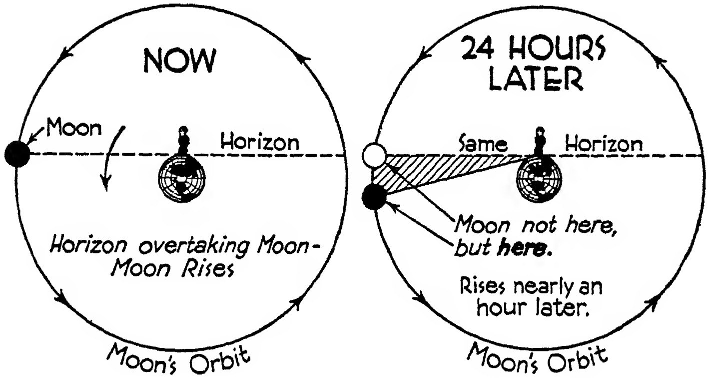


FIGURE 14. Why the moon rises later every night. The earth must execute considerably more than one complete rotation in order that the horizon may again overtake the moon as the moon advances in its orbit around the earth.

strictly new the moon sets with the sun. Successive passages between the earth and the sun give us our succession of new moons; and since the line from earth to sun steadily advances as the earth moves in its orbit we have our old story of running laps against a moving finish line. Thus there is no conflict between the two figures given above.

Rotating, then, 27.32 times as slowly as the earth, the moon produces a very small centrifugal effect. If the two bodies were of the same size, the moon's surface speed would be about 1/27 of that at the same latitude on earth. But the distance around the moon is smaller in the ratio of 1 to 3.66; both factors together give a surface speed almost exactly a hundredth as great as the earth's.

Squaring 100 (the force is proportional to the square of the speed) we get 10,000; and dividing by 3.66 (the force is inversely proportional to the radius of the circle) we find our final result, 2730. The centrifugal force at the earth's surface is 2730 times as great as that on the moon. Even in proportion to weight the earth's effect is larger in the ratio of 450 to 1. Clearly, the atmosphere was not lost by centrifugal action. The moon did not throw it off.

Escape of Atmospheres

Then the moon's atmosphere must either have been completely used up, as by chemical combination — an extremely improbable hypothesis — *or it must have left of its own accord.* A pound of air weighs as much as a pound of stone; but the evidence shows that although the moon can hold the stone with a wide margin of safety it cannot hold an atmosphere. A calculation based on the law of gravitation shows that at the moon a speed of 1.48 miles per second would enable a body to go beyond the moon's gravitational grasp. It would escape. Therefore the moon's atmosphere must have attained an outward velocity at least as great as 1.48 miles per second. Since the atmosphere as a whole could hardly have reached that speed except as a result of a celestial catastrophe so violent that the moon itself would have been shattered and the fragments dispersed, we conclude that gas molecules may individually attain speeds as great as 1.48 miles per second.

Here, perhaps, is a curious argument; yet if this conclusion had antedated all experimental evidence of molecular motion it might have opened a new field; the moon a clue to the molecule. Major discoveries have resulted from less. History took a different turn: the moon's lack of an atmosphere was not explained until an analy-

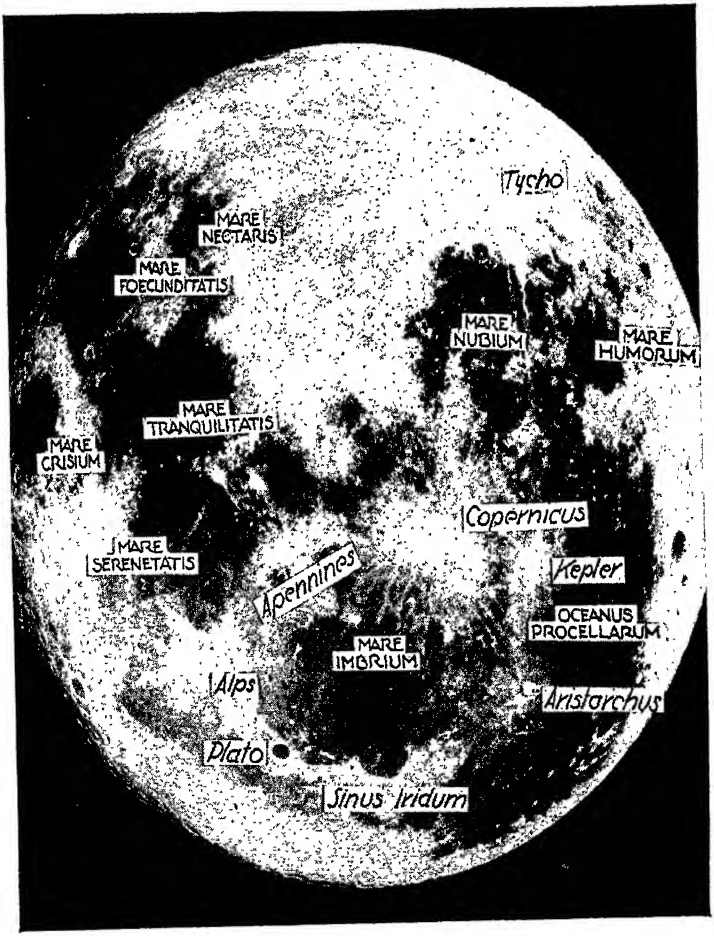


FIGURE 15. A Yerkes Observatory photograph of the moon. The moon is approximately full and is shown inverted and reversed, as seen through the inverting telescope. For field glasses and prism binoculars, turn the page upside down.

sis of experimental data had shown that gas molecules do indeed move at tremendous speeds.

Molecular Motion

A very few facts about molecules will satisfy the requirements of our present problem. No microscope can form an image of a molecule, the waves of visible light being too long; but if one observes a smoke particle in the air through a good instrument he sees in its erratic dancing evidence of a molecular motion that is both vigorous and chaotic. At a given instant more molecules strike the smoke particle from one direction than from the opposite, and it responds bodily to the small excess of force. This is the well-known Brownian movement.

In the Crookes radiometer, a device often seen spinning in the sunlight in opticians' windows, the air molecules rebound more vigorously from the blackened face of each vane than from the opposite, polished surface; hence the vanes recoil, the black sides receding. Within the glass globe of the radiometer there is nearly a perfect vacuum. If it is the best vacuum obtainable by present artificial means — our nearest approach to nothing — it contains about five billion molecules of air in every cubic inch, a number two and a half times the population figure for the world. Yet all except one out of every hundred billion molecules that originally filled the space at normal pressure have been removed. Being so numerous, they must be small. To speak of the size of a molecule implies a knowledge of its surface. The molecule, as we shall see later, is itself largely empty space, an aggregation of still smaller particles distributed at wide intervals. It has no definite surface, yet occupies a certain space. In the case of oxygen the space per molecule is such that 70,000,000 in a line would require an inch.

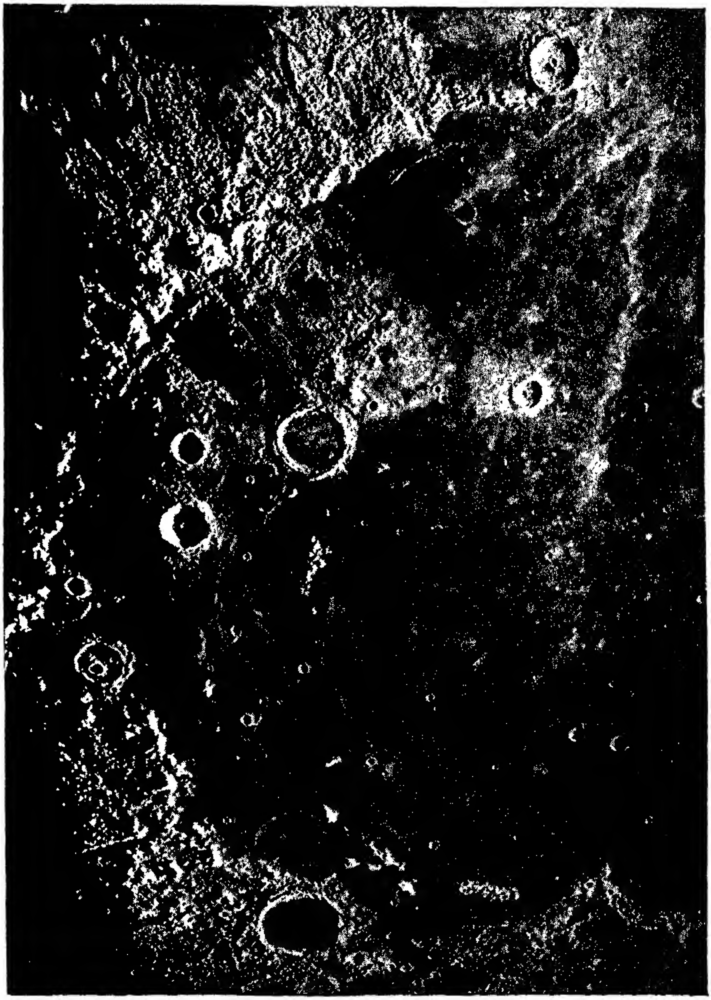


FIGURE 16. The Moon at last quarter, region of Mare Imbrium. This large dark area is bounded at the upper left by the Apennines, at the lower left by the Alps. See the labeled key photograph, Fig. 15. (Photographed at Mount Wilson Observatory.)

The molecules of a gas dart to and fro at various speeds, bumping into one another and against the walls of the container. In an automobile tire it is this violent beating from within that keeps the tire walls from collapsing under the weight of the car. In oxygen at the temperature of melting ice, the most probable speed is one-quarter mile per second. About 40,000 out of every million have speeds greater than twice that value. The great gun with which the Germans bombarded Paris from a distance of 75 miles imparted to its shells a muzzle-velocity of about a mile a second, a speed slightly less than the most probable velocity of hydrogen molecules at usual room temperatures. About 40,000 of every million hydrogen molecules travel faster than two miles per second. Many move more slowly, many faster, and the general level of velocity rises with the temperature. A mile-a-minute wind is a hurricane; yet the average molecule in our atmosphere is moving many times that fast. If all the air molecules ever came to move in the same direction they would mow down everything on the face of the earth. But they always move helter-skelter in all directions.

So the moon must have lost its atmosphere because the molecules moved too fast for it. Endowed with a certain size, a certain mass, the moon carried in its own body the necessary conditions of failure to hold an atmosphere. It could exert just so great a gravitational attraction, and that was not enough. Its fate was sealed when it was formed. The swiftest molecules left almost immediately, then, gradually, the others. One by one they found themselves moving in the right direction with the requisite speed, and they simply kept on going. The first to leave aided, indirectly, those left behind: for as the atmosphere grew thinner the sun's rays beat down more fiercely on the now poorly shielded surface. The moon's guard was dropping, and it was a better target for the sunlight. Daytime temperatures rose accordingly, increasing the

FIGURE 17. The Moon, region of Copernicus. The area below Copernicus is part of Mare Imbrium. The extreme tip of the Apennine range is seen extending to a prominent crater at the left, slightly below the middle. See the labeled key photograph, Fig. 15. Use diameter of Copernicus (56 miles) as a scale in estimating sizes of other features. (Photographed at Mount Wilson Observatory.)

molecular speeds; until finally all had attained or exceeded 1.48 miles per second and the moon was left to travel through the heavens a barren body, utterly incapable of supporting any of the forms of life that we know, and no doubt today surgically sterile.

Conditions on the Moon

For lack of an atmosphere the moon undergoes severe extremes of temperature. Its average distance from the sun is of course the same as the earth's, and it intercepts the same amount of radiant energy, square mile for square mile, as does the gaseous envelope of the earth. Yet soon after sunrise the unprotected surface of the moon reaches approximately 200 degrees Fahrenheit. When the sun goes down the opposite effect immediately sets in, the surface layer radiating its heat away through the vacuum above it and cooling rapidly to a night temperature of approximately 150 degrees below zero Fahrenheit. Day after night, night after day, these changes of temperature repeat themselves with unremitting rigor, their severity augmented by the slowness of the moon's rotation on its axis. For two weeks, on the average, the sun shines continuously on a given spot, then follow two weeks of night and unrelenting cold. When, looking at the crescent moon, we reflect that on the bright side of the curved line which separates night from day the ground is as hot as boiling water is here, and on the other side 350 degrees colder, we realize how different the conditions would be on earth if we had no atmosphere.

No sound! The moon is a place of uncanny quiet. The ground would vibrate if a landslip brought the top of a mountain crashing to the plain, but there is no air to transmit sound. To witness the impact of a meteorite, which here makes an appalling roar, would be like looking through a window into a sound-proof room when violent happenings were in progress.

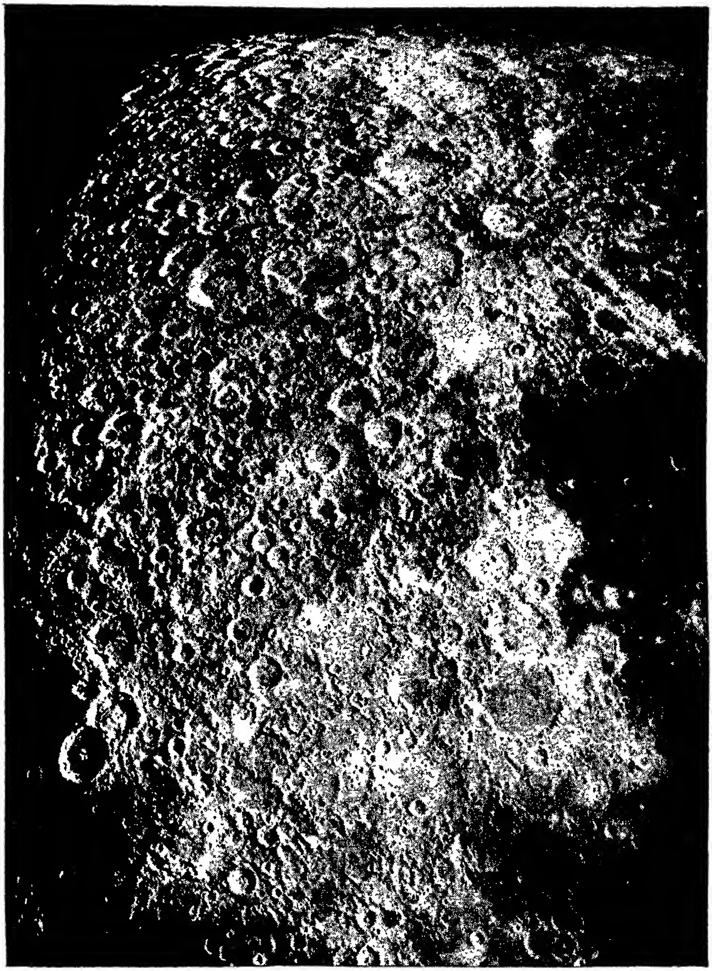


FIGURE 18. The Moon, five days after the full phase, region of Tycho. A bright ray system radiates from Tycho. See the labeled key photograph, Fig. 15. The moon's south pole is near Tycho. The sunset line is at the left. Note the shadows cast by the lofty crater walls. (Photographed at Mount Wilson Observatory.)

There is no wind on the moon. If you climbed up a crater wall to the top of one of those sheer precipices which we see with our telescopes and balanced a sheet of paper on an overhanging point of rock, it would never be blown away. It would remain there until it disintegrated in the heat and light of the sun, or until thermal expansion and contraction caused either it or the rock to slip, or until a meteor or perhaps the lunar equivalent of an earthquake (should we say moonquake?) disturbed it. And if a quake dislodged the rock, the paper would not flutter during a free fall, but would keep pace with the falling rock.

There is no weather on the moon, hence no erosive weathering. For what is weather but the condition and the actions of the atmosphere — the wind and the rain, lightning and thunder, the falling of snow, the forming of ice, the humidity and temperature of the air? There are no rivers or waterfalls to cut canyons through the mountains, to make fertile valleys and build up deltas; no rain to wash, and no wind to blow the soil; no glaciers grinding solid rock; no lakes or oceans whose waves might carve out shores. There are no roots to loosen soil, and no water to freeze in rocky crevices and by its expansion slowly break up stone and form new soil.

Earthquakes and landslips are possible. Volcanic action may occur. The large variations of temperature must produce severe strains as a result of expansion and contraction of the surface layers. A half-billion or so of meteors strike into the moon's surface yearly at speeds ranging up to 44 miles per second, there being no cushioning atmosphere to vaporize them and transform them into harmless shooting stars; and occasionally great meteorites must add at least a few small craters to those which already make the surface of the moon look pockmarked.

Yet in all the three hundred and more years since Galileo laid the

foundations of selenography, no surface changes large enough to be detected with certainty have been seen. There have been some disputes about the evidence, and one must remember that telescopic photographs of the moon have been accumulating only since 1850, a period very short when measured by the geologist's or astronomer's calendar. This much we can say: when one enjoys that most beautiful of celestial sights, a telescopic close-up of the moon, he sees in the jagged mountain ranges, in the lofty peaks, the high plateaus, the broad plains, and the sharp crater walls, the enduring features of a place where the commoner forces of erosion have long since ceased to act.

Surveying the Earth's Atmosphere

So much, at present, for the consequences of a deficiency of gravitation. The moon serves as an object-lesson to shed light on our own environment. Let us see how thick an atmosphere the earth's superior attraction can retain. The reader may invent his own conveyance: the best stratosphere balloons would not carry us more than a fraction of the way. We pass through the lower clouds very quickly, pausing for a moment, however, at the mile-and-a-quarter level to take the temperature of the open air. It is 32 degrees Fahrenheit, the normal freezing point of water.

Three and a half miles above sea level: Here in the midst of the cumulo-nimbus cloud region we have attained an altitude only a third of a mile less than that of the summit of Mt. McKinley, in southern Alaska, the loftiest point in North America. Our barometer, which read 30 inches when we started, now reads 15. We have left half of the atmosphere behind. We are not halfway to the top; but all the air above us weighs only as much as the 3.5-mile layer already traversed.

The temperature of the outer air is four degrees below the Fahrenheit zero. We thrust an electrically heated pot of water into the open: it boils at 179 degrees, 33 degrees below the normal boiling point at sea level. It boils readily because there is less air pressure to hinder the bubbles of vapor from forming. In high altitudes pressure-cookers are commonly used, to prevent boiling from occurring before the water is hot enough to cook food properly.

Five and a half miles up: Here we are on a level with the top of Mt. Everest, an unconquered peak which rises from Tibet at the Indian border, four hundred miles north of Bengal Bay and five and a half above it, the highest point on earth. No man has ever set foot on the top of Mt. Everest, though many have climbed until they left their bodies to be preserved in the perpetual snow drifts near the top. The barometer reads a fraction over nine inches; the thermometer 45 degrees below zero.

Six miles: The kite limit. Temperature 56 below. The air is steadily getting thinner.

Seven miles: The stratosphere begins. More than three-fourths of the atmosphere is now below us. The temperature is 67 degrees below zero, Fahrenheit. There is no dust in the air, and a negligible amount of water vapor. The clouds have been left behind.

Eight miles: The airplane altitude record. The temperature has ceased to fall: it is still 67 below.

Fourteen miles: The highest man has ascended. The blue sky has been left behind. The American stratospherists, returning from their record climb late in 1935, reported a sky almost black at this level, a black-violet sky differing very little from night, though the sun was shining brightly. Turning our backs to the sun at this level we see the brighter stars. The blue of the sky is of course merely sunlight scattered by the particles and molecules

comprising the lower atmosphere, a depth effect like the blue-green of deep clear water.

Twenty-two miles: The greatest altitude that sounding balloons carrying instruments have attained. They carry no observers, but drift back to earth bringing samples of air and records of temperature and pressure. The temperature here is 67 degrees below zero, Fahrenheit, just as it has been all through the stratosphere.

Twenty-five miles: This is the farthest from the earth that anything has knowingly been thrown. It was into this thin air, 250 times as rare as the air we breathe, that a giant shell rose on its way to Paris on Good Friday in 1918. In this thin air the shell rounded the crest of its path and turned down to reach its goal in the crowded church of St. Gervais. Man's greatest triumph over gravitation — and an item for philosophers! Two hundred and seventy-three pounds of steel went hurtling twenty-five miles above the earth, its three-minute path calculated by astronomy to allow for the change of latitude and the spinning of the earth while it was on its way — all to the end that tons of falling masonry might crush the unsuspecting people who were kneeling in a church seventy-five miles away. For five weeks shells like that rained down on Paris.

We thrust some water out into this cold and almost airless region. It boils instantly without being heated, and keeps on boiling until it is frozen. The thermometer reads 67 below, and the barometer — read only with difficulty — eight one-hundredths of an inch. All the air now left above us does not weigh as much as a film of mercury a tenth of an inch thick.

Forty-seven miles: The top of the atmosphere, as judged by the duration of twilight down on the earth. After the sun has set its rays continue for a while to strike the air above the observer's

head, producing the pleasant afterglow called twilight. The same action gives the light of dawn before sunrise. But above the height to which we have now ascended, there is not enough air to scatter down a noticeable amount of light.

One hundred and twenty-five miles: The top of the atmosphere, as judged by meteors, or shooting stars. The meteors are in our atmosphere when we see their bright streaks across the sky. These small bits of stone, iron, nickel, and other materials travel in space around the sun. A single observer sees only those which reach the air in his own vicinity, and at night; but the total number plunging into the earth's atmosphere in 24 hours is some twenty millions. By sighting their bright streaks from the two ends of a measured base-line astronomers apply the ordinary triangulation method of surveying to measure how high meteors are when they begin to shine, and thus discover how far the atmosphere extends in a sufficient density to heat the meteors to incandescence by friction. Most meteors do not begin to shine until they are within a hundred miles or less, but a few have been seen as high as 125 miles. Higher than that, even the swiftest meteors meeting the earth head-on do not encounter enough air molecules to become luminous.

In addition to the sporadic daily bombardment, showers of meteors occur at dates which are repeated year after year, showing that certain meteors travel in swarms around the sun. Observers planning to stay up late at night to watch for a meteor shower may sometimes profit by trying the night before, and the one succeeding, as well as the date announced for the display, and even so should be prepared for disappointment. There are always more meteors than usual at the regular shower-date, but one cannot at present foretell in which year the earth will intercept the swarm of meteors at a place in their orbit where they are most thickly crowded.

Occasionally a large meteor strikes the earth; what remains is called a meteorite. Admiral Peary brought one back from Greenland that weighed 36 tons, mostly iron. A meteorite of great size buried itself in northern Arizona, making a deep crater three-

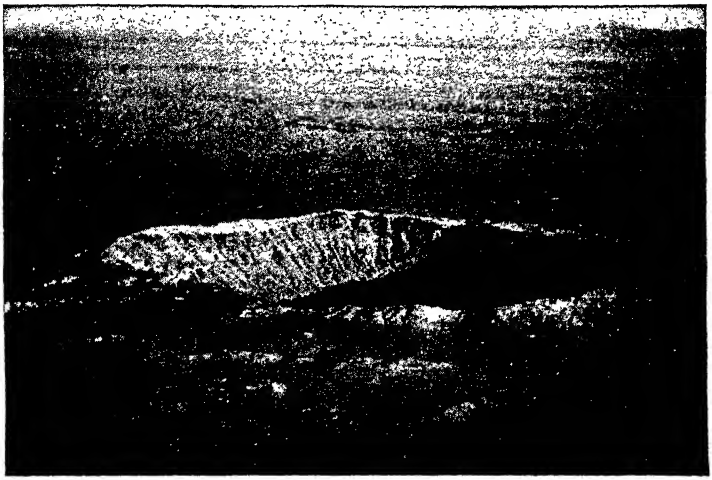


FIGURE 19. Meteor Crater in Arizona, near Cañon Diablo. (Photographed by Clyde Fisher.)

quarters of a mile across near Cañon Diablo. Another famous visitor from space destroyed several square miles of forest in northern Siberia in 1918. Upon being analyzed chemically meteorites prove our kinship with extra-terrestrial matter: they contain no substance with which we are not familiar.

Six hundred miles: Here we reach our goal. There must be stray molecules farther still, indeed some of the swiftest molecules escape; but above 600 miles there is not enough air to produce the aurora borealis, the northern lights, or their counterpart in far southern latitudes, the aurora australis. Most displays occur lower than 200 miles. Electrified particles, probably from the sun, strike

into that thin air and make it glow, an effect which we imitate (and improve upon) with our electric tubes.

So take the longest straight line that can be drawn between the extreme corners of Florida, stand it up on end, and it reaches to what we shall call the top of the atmosphere. If one left his imaginary craft at that height to make a quick trip back, what would happen? Let us not linger over the boiling, the freezing, the parachute that would not catch enough air at first to open. Yet without a parachute one would almost become a meteor himself. Almost, not quite. After several hundred miles, and several minutes, of falling, the gradually thickening air would get in its work. He would not quite attain the astronomical glory of a shooting star.

Escaping from the Earth

There at the top of the atmosphere the earth's attraction is only 25 per cent less than at the surface of the earth. If the shell from the Paris gun had been directed upwards towards the zenith it would have risen less than sixty miles before the invisible finger of gravitation turned it around. But if it had been launched upwards fast enough to retain a speed, after passing through the lower atmosphere, of 6.95 miles per second, approximately six times as fast as it actually did travel at the moment on that Good Friday when the gun belched it forth, it would have continued on its way. No man would ever have seen it again, unless —

Let us not be too sure. That bit of steel would go revolving around the sun, rotating on its axis, making its own day and year, its own sunrise and sunset, imitating in its puny way the majesty of a planet; and after centuries or ages it might possibly cross the earth's path, perhaps in the dead of night, and bring to

the lips of a stargazer in that far-off time the familiar words, "See the pretty shooting star." One may infer from this the ultimate fate of the moon's atmosphere. It has simply increased the amount of debris that litters the solar system. Unnumbered billions of small bodies ranging in size from molecules to meteorites circulate in orbits under the sun's gravitational control, each traveling its solitary way until, deflected by competing attractions, it joins forces with a planet and perhaps makes a streak of light in the sky to celebrate the event. To start from the earth and escape from the sun requires an initial velocity of 26 miles per second; an object launched that fast would, after several hundred centuries, enter the region of the stars.

Sunset Phenomena

Within the atmosphere, and produced by it, occur many familiar optical effects. The blue of the sky; the rainbow; the colored rings a few degrees in diameter sometimes seen encircling the moon or the sun, a diffraction effect caused by fine water particles; the larger rings some 45 degrees in diameter, the result of refraction of light by ice crystals hovering in the upper air; the bright streaks of meteors; the apparent redness and oval shape of the setting sun; the twinkling of the stars, an illusion similar to the unsteady appearance of objects when viewed through the air currents ascending above a hot stove or pavement — these are the result of atmospheric action and thus indirectly due to gravitation, which keeps this atmosphere of swift-moving molecules bound almost as securely as though the earth were roofed with a hermetic seal.

A moment's thought shows that the sun itself does not grow red when setting. What an extraordinary coincidence it would be

if that great body changed its color exactly in step with the spinning of the earth ninety-three million miles away! To clinch matters, the sun sets at Portland, Maine, about three and a half hours before it sets at Portland, Oregon, and could hardly be both red and white at the same time.

White light is not one color, but a blend. The raindrops which produce the rainbow analyze sunlight by refracting the different colors or wave lengths differently and thus setting them side by side in a curved spectrum. The order is: Violet, Indigo, Blue, Green, Yellow, Orange, Red; the initials form the pronounceable word Vibgyor. With two glass plates, one deep red, the other deep blue, one can readily show that white light is a mixture. Look at a white cloud through the blue glass: it appears blue. Therefore white must contain some blue. Through the red plate the cloud appears red, hence white contains some red. Looking through both plates at once we find that the combination filter is opaque, or nearly so. One plate transmits the red and absorbs the blue and other colors; the other does the opposite, absorbing red and other colors and transmitting blue. Therefore together they absorb all, or nearly all, of the wave lengths of white light, and the combination is black, or opaque. With a larger variety of colored filters one can find many interesting combinations.

Thus if we rob sunlight of one color we see the effect of the remaining colors. The atmosphere is not perfectly transparent. It absorbs (and also scatters) all the visible wave lengths to a certain extent, but blue most of all. The fact that the sky is not white, but tinged with blue, shows that the air scatters blue more strongly than the other colors. The blue that we get from the sky has been stolen, so to speak, from the direct beams of sunlight, and the greater the mass of air through which the sun's direct beam must pass to reach the eye, the greater its loss of blue.

If the reader will imagine his eye placed on the rim of a wheel at the bottom of a layer of cellophane which has been wrapped around the rim to simulate our atmosphere on the earth, and then picture how much more cellophane he would have to look through along a tangent than if he sighted straight up through the thickness, he will understand why the setting sun (also the rising sun) appears red. When it is close to the horizon its light travels much farther through air than when it is high in the heavens, hence the direct beam to our eyes is robbed of more of its blue. This loss of the blue leaves the red predominating.

A different action of the atmosphere causes the setting sun to appear oval, nearly lemon-shaped. As the sunlight passes into and through the atmosphere it is refracted, or bent, in such a direction that the entire sun seems to be higher in the heavens than it really is — an effect somewhat similar, though not entirely, to the apparent lifting of the bottom of a pool of clear water by refraction, which makes it appear shallower than it really is. The rays from the bottom of the sun strike the air at a slightly different angle than do those from the top, and are bent the most. Therefore the bottom of the sun seems to be lifted more than the top, and the sun looks as if it had been squashed.

To an observer on the moon the sun would remain white and round while setting, and the sky would appear, as always, black. The sun would set slowly, requiring almost an hour at the equator to get its whole body across the horizon; but once its upper edge had disappeared sunlight would cease instantly. There are no clouds to catch the light for a while longer and make a billowing ocean of color in the sky. Two weeks later the sun would rise without warning — and all the time, day and night, the same constellations of stars that are familiar to us could be seen shining steadily, never twinkling, in a black sky.

The Sun's Gravitational Attraction

More than the beauties of a sunset sky would be lacking if there were no gravitation. Gravitation enables us to *have* a sun. The same principles of inertia and centrifugal force heretofore discussed lead us to realize that in the absence of a suitable force the earth would not continue to revolve around the sun.

The centrifugal force depends on three quantities: the mass of the moving body; its speed; and the radius of the curved path in which it is traveling. Newton's discovery of gravitation enabled us to find the first of these quantities, the earth's mass. Cavendish simply compared the weight of an object, which is the earth's pull on it, with the attraction of another object of known mass.

The second quantity, the earth's speed, is found by measuring the apparent annual displacements of the stars from their true positions. This is an effect due to the *aberration of light,* and is similar to that observed when one is moving through the rain. The observer's forward motion causes each raindrop to strike him at such an angle that it appears to come from a point ahead of its true source. As the earth moves around the sun, at one moment the light from a star seems to come from a point slightly ahead of its true position; and six months later the same effect occurs, only now the earth is on the opposite side of its orbit and *ahead* is in the opposite direction. Thus the stars appear to move back and forth as the earth circles the sun. By measuring this minute annual displacement of a star, and knowing the speed of light as a result of laboratory measurements, the speed of the earth can be determined very accurately. It is 18.5 miles per second, a very creditable rate for this old earth to be moving. Figure how far you go while reading this page.

Lastly, knowing the earth's speed we can calculate how far it

travels in a year, which of course is the distance once around its orbit; and knowing this we can quickly determine the distance to the center, which is the third and last of the three quantities we needed to know, for this is the radius of the earth's curved path. Some small corrections are needed in order to allow for the fact that the earth's orbit is not perfectly circular but slightly elliptical, or oval-shaped.

Thus the earth's centrifugal force can be found — not that due to its spinning on its axis, but the vastly larger force caused by the movement of so great a mass at the high speed of 18.5 miles per second in a curved path. This force, obviously, is equal to the gravitational attraction which the sun exerts on the earth; if it were not, the earth simply would not be moving as it does. (Incidentally, it was a knowledge of this force, together with the earth's mass and its distance from the sun, that permitted calculation of the mass of the sun by the law of gravitation; the result was given earlier, 332,000 earths.) Resuming our argument, we know this centrifugal force and can express it in tons-weight, pounds-weight, grams-weight, or dynes; but the quickest way to gain some comprehension of its magnitude is to see how thick a material connection would be needed to hold the earth to the sun just as one might hold a ball by swinging it around in a circle on the end of a string.

A steel cable suitable for moving houses would not do, nor a pole as thick as one of the giant redwoods of California. To hold the *moon,* the earth attracts it with a force which would pull asunder a round steel shaft about 250 miles in diameter, and a much greater force is needed to hold the earth in its orbit. The sun attracts the earth with a force that would rupture a steel shaft 3340 miles in diameter, a solid shaft of nearly half the earth's diameter. Even if a super-construction crew came in from space,

bringing its own tools and materials, to put that much steel in place to tie the earth to the sun, it would not be a substitute for gravitation. It would fly to pieces under its own centrifugal force. How so great a force can be transmitted through 93,000,000 miles of vacuum, who can picture? Albert Einstein has given an answer, but to give it he proposed curved space, which is not visualizable. Let us leave it, for the moment, a mystery — though really no greater a mystery than how the earth can make the reader of this page fall to the floor when he slips off the edge of the bed.

The Sun's Radiant Energy

Without this force that holds the earth a prisoner to the sun, the earth would move in a straight line into the depths of space. On and on it would go, traveling some eighteen times as fast as the Paris shell, straight into the region where the stars abound. Behind it the receding sun would grow smaller, until at length the sun became one of the stars, a speck of light in the universe. And what of conditions on the earth? What that we have would be lost on such a journey?

At a distance of 93,000,000 miles one cannot look directly at the sun without damaging his eyes. Every square inch of its surface is shining with the luminous power of nearly a million and a half candles. A small fraction of this flood of light bathes the planets and their moons, but most of it speeds on past them at the rate of 186,000 miles per second. Four and three-tenths years after leaving the sun, some of the light strikes the triple star, Alpha Centauri. In 8.8 years some sunlight reaches Sirius; in 400 years Polaris; in 30,000 years, the globular cluster of a million stars in Hercules; and 900,000 years after being radiated a bit of sunlight

will fall on the Great Nebula in Andromeda. Most of it may still be traveling.

The earth's small quota of all this sunlight is ample for our needs. Our eyes respond, our skins respond, the chlorophyll of

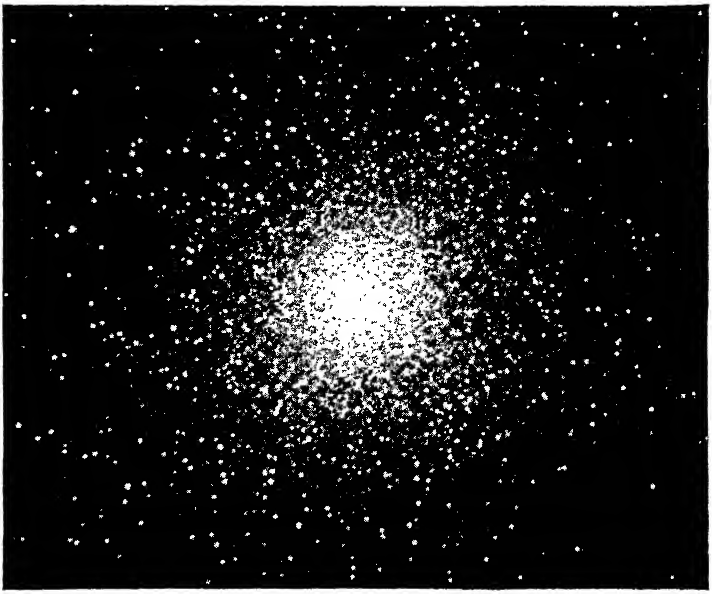


FIGURE 20. The globular cluster in Hercules. Barely visible to the naked eye, this cluster contains more than a million stars. Its distance from us is approximately 30,000 light-years. (Photographed at Dominion Astrophysical Observatory.)

the plants converts it by photosynthesis to feed and beautify the world and to maintain our supply of oxygen. The light of electric lamps is traceable to sunlight. The energy of these lamps comes from the coal, oil, water power or wind that turned the generators. Coal is the sun-made vegetation of remote ages preserved by fossilization. Petroleum, too, came from vegetation.

The energy of windmills is the energy of the sun's radiation that warms the air and makes it move, and water power results from the flowing of the water back to sea after the energy of the sun has lifted it up and deposited it on the heights.

Of all the energy that the sun radiates, one part in two billions strikes the outer atmosphere of the earth. Nearly half of that is reflected back into space. When we view the old moon in the new moon's arms we see the dark part by sunlight reflected to the moon from our atmosphere. Energy gets through to the earth's surface at a rate which, averaged over day and night, equals two and a half million times the power of all the running water already harnessed.

If this energy were completely utilized, every square mile of the earth's surface, solid and liquid, could keep sixteen thousand engines running day and night at forty horsepower. At four cents per kilowatt-hour, the bill for all this energy would be slightly more than a billion dollars a second, or $2000 an hour for every man, woman, and child, civilized or savage, in the world. At Niagara or other of the great waterfalls of the world the visitor becomes silent as the mighty release of energy at his feet produces its psychological effect; he may well reflect what the whole amount of our solar energy could accomplish if it were wisely used.

And what of the earth that we imagined leaving the sun for lack of gravitation? In six years, traveling eighteen and a half miles every second, it would reach the distance of Pluto, the outermost known planet of the sun's family. Looking back (but all the inhabitants would be dead) one would see an insignificant sun. In those six years the sun would have appeared to shrink until it covered one sixteen-hundredth as large a fraction of the sky as when the journey began. The amount of light and heat falling on the earth would have been reduced 1600-fold. The

surface temperature would have fallen to approximately 370 degrees below zero, Fahrenheit. Oceans would be solid, all life gone. We see how pleasant a place the planet Pluto must be. A few years more, and the earth's surface would be very nearly at the absolute zero of temperature. Only the stored-up warmth in the core, and the heat regularly produced by the atomic explosions of radium, uranium, thorium, and similar elements, would keep the earth from being absolutely cold as it traveled towards the stars.

What is the source of the sun's energy? How can it continue to radiate so prodigally without cooling? Or is it cooling? These are interesting questions; but our underlying theme in this unit is gravitation, and we conclude with a short chapter showing that gravitation, which holds us on the spinning earth and endows us with an atmosphere, a moon, and an energetically radiating sun, was also responsible, as best we can tell, for the existence of the earth itself.

Chapter 4

THE ORIGIN OF THE SOLAR SYSTEM

If we are going back to origins in an effort to discover what part gravitation may have played in the formation of the planets, the first step, logically, is to find how far back we need to go. How old is the earth? Merely to pose the question in the hope of a supportable answer presupposes a philosophy which was a long time in the making.

Nearly a century before Galileo was in his prime another great Italian, Leonardo da Vinci — painter, sculptor, physicist, biologist, engineer, architect, philosopher — dug out fossils, speculated on their age and history, and envisioned nature as being controlled in an orderly manner by natural law. "Necessity," said Leonardo, "is the bridle of the universe; know the law and henceforth you will have no need of experiment." The year of Galileo's death (and Newton's birth) found René Descartes, French philosopher, mathematician, and physicist, elaborating a clear-cut dualism which divorced mind from matter and left the world of the latter to be explained solely by mechanical actions. The sweeping universality of Newton's principle of gravitation gave a tremendous impetus to an intellectual movement which was already well under way. Newton's success seemed to suggest that by observation and analytical thinking the universe could be reduced to one logical and harmonious whole. The present came to be viewed as the inevitable product of the past, and man sought to reconstruct the steps. More than curiosity, more than a desire for background and perspective was involved: to unravel the past meant to find the explanation of the present and perhaps a clue to the future.

Astronomers first, then geologists, then biologists built evolutionary structures which challenged the attention of mankind. All turned in the end to physics and chemistry for a dependable estimate of the length of time that had been available for their evolutionary schemes to fulfill themselves—but not before physics, overconfident, perhaps, as a result of its position as pacemaker in the search for mathematically exact and general laws of nature, had made an historic mistake.

The nebular hypothesis of the origin of the solar system has already been mentioned. Thomas Wright published speculations on this subject in England in 1750, and these, falling a year later into the hands of the German philosopher, Immanuel Kant, led him to publish, in 1755, the theory which Laplace developed more fully in 1796. During this period two Englishmen, James Hutton and William Smith, were laying the foundations of the science of geology. Smith attempted to deduce the relative ages of the rocks from their fossilized contents; and in 1830–33 another Englishman, Sir Charles Lyell, published a clear-cut evolutionary hypothesis to account for the stratification of the rocks observed in the surface layers of the earth. Jean Baptiste de Lamarck, a French contemporary of Lyell's, pioneered in the field of biological evolution. On his heels came four famous Englishmen: Charles Darwin, Alfred Russel Wallace, Herbert Spencer, and Thomas Huxley. Darwin's "Origin of Species" appeared in 1859, a landmark in the history of thought.

The Age of the Earth

The question of the earth's age was now to the fore. Geologists, loath as many of them were to shock their contemporaries by suggesting an age which seemed utterly fantastic at the time, esti-

mated conservatively that upwards of 100,000,000 years had been required for the formation of the layer-on-layer structures of stratified rock which lay exposed to their gaze in many parts of the earth. Surely, they said, the slow transportation of silt by wind and rain, and its slow hardening, could not build up any sooner than that these immense thicknesses of stratified rock. Even that great age scarcely allowed the additional time for rivers to carve canyons through the rock *after* the oceans or lakes on whose bottoms it had formed had disappeared. And what of the mountains and plateaus which had disintegrated as a result of erosion? At the instance of geologists, chemists analyzed first sea water, then the waters of various rivers, and estimated how long water must have been running into the oceans at approximately its present rate in order to make the oceans as salty as they were. Flowing water dissolves salt from soil and rocks and carries it to sea, where it remains while evaporation produces more rain to replenish rivers which bring more salt. Thus the oceans grow saltier and saltier. The results agreed reasonably well with the estimates based on rocks.

To many of the biologists 100,000,000 years seemed a small allowance. Digging deeper, finding older and older fossils, they concluded that the higher forms of life had taken much longer to evolve from the earlier primitive types. Thomas Huxley, who called himself Darwin's bulldog, boldly estimated that biological evolution had been in progress for a billion years.

William Thomson, afterwards Lord Kelvin, decided to settle the question by the accurate calculations of physics. The earth's temperature was known to increase with depth at the rate of approximately one degree Fahrenheit for every 60 feet of descent. If the interior of the earth was warmer than the surface, heat must be flowing from within and escaping. Thomson concluded that

the earth was cooling, and in 1862 calculated that not more than 200,000,000 years had elapsed since the earth was a molten mass on which a solid crust was beginning to form.

This result was not at first unsatisfactory to the geologists, though to Huxley it seemed inadequate; and as further data came to light geologists, too, began to believe that the earth must be older. Yet in 1899 Lord Kelvin announced a new result, much smaller. In 1854 the German scientist von Helmholtz had developed the contraction hypothesis of the sun's heat, a theory which viewed the sun as gradually shrinking under its own gravitational attraction and thus replenishing its supply of heat, just as the air in a tire pump grows warm when compressed; and on this view Kelvin stated that even if the sun had contracted from beyond the outermost planet the time required would have been from twenty to forty million years, no longer. In that period, then, all earth-changes must have occurred.

Physicists dismissed the objections of geologists and biologists rather arbitrarily at first. Lord Kelvin lies buried beside Sir Isaac Newton in Westminster Abbey, so great were his contributions to physics, both pure and applied; but in this problem faith in hypotheses and too small a regard for the results of other sciences led him astray. At one stroke the newly discovered phenomenon of radioactivity removed the foundations on which both of Kelvin's calculations rested. A source of energy hitherto undreamed of was available in the universe. Atoms of radium, uranium, thorium and similar materials were exploding within the earth's crust, liberating great quantities of heat. Thus the earth might not be cooling as Kelvin had assumed in his first calculation; and if atomic energy were being similarly released in the sun the result based on the contraction theory was also invalid.

By a curious coincidence, the very discovery that undermined

the earlier calculations solved the problem. Atoms cannot explode unless they have parts, and the parts into which atoms of uranium and thorium eventually disintegrate are found to be atoms of lead and helium. The old dream of the alchemists, the transmutation of elements, was thus realized; though in radioactivity we find costly substances turning into baser, not lead into gold. Every second a certain fraction of the number of atoms of a radioactive specimen explode. This fraction is determined very accurately in the laboratory. Thus a quantity of uranium or thorium which was sealed in a rock when the earth's crust solidified serves as a recording clock, its silent ticks the explosions of atoms, the record the lead and helium which accumulate slowly but with mathematically precise regularity. The rate of transformation is at present as far beyond man's control as the movements of the planets in their orbits. Heating, cooling, the action of acids, high pressures, exposure in a vacuum—by no means, however violent, has the rate of disintegration been altered artificially.

The lead produced by radioactivity is readily identifiable. Ordinary lead has an atomic weight of 207, while lead produced by uranium and thorium has atomic weights of 206 and 208, respectively. The experimental work is of course very delicate; but since the tiny projectiles expelled in the atomic explosions are electrically charged the superior sensitivity of electrical methods is available. By suitable amplifying devices a single charged particle shot from a radium atom can be caused to record its presence automatically by jogging a magnetic pen that is making an ink trace on moving paper. Rocks dug from many parts of the earth's crust have been subjected to radioactive analysis. The ratio of the accumulated lead to the radioactive material remaining undisintegrated is determined, and calculating back one can discover how long a period has elapsed since the rock solidified.

Results obtained in different parts of the earth agree surprisingly well. The ages of rocks of different geological periods are determined. A vast quantity of numerical data has accumulated. We note merely the final conclusion. The earth is older than 1,000,000,000 years and not as old as 8,000,000,000 years. Possibly narrower limits can safely be assigned, but let us not make the error of claiming too high an accuracy in the face of the delicacy of the measurements and the length of the period involved. Authorities in all fields of science accept these limits for the age of the earth.

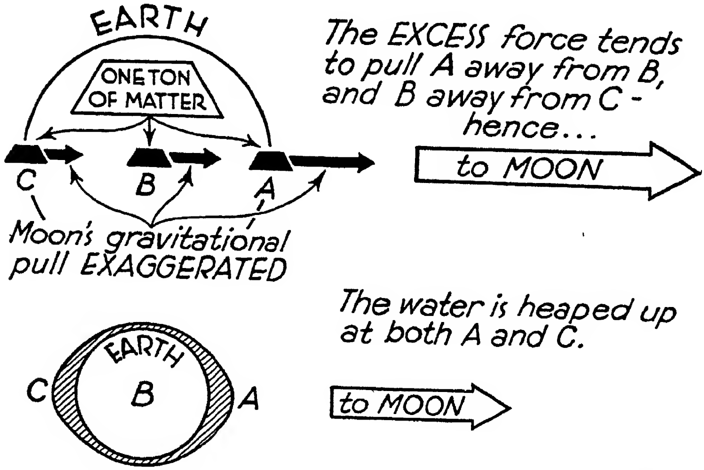
Gravitation Produces Tides

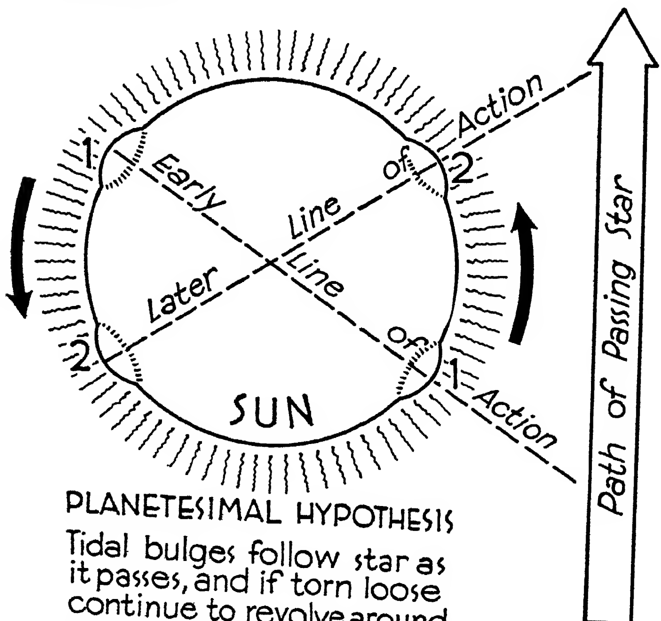
What caused the earth to be formed at some time between one and eight billion years ago? We cannot say with certainty. We can, however, picture an action which must occasionally occur in the universe and which, if it had befallen the sun, could have produced the earth and our fellow-planets. This action is nothing more nor less than the raising of a tide on so grand a scale that the rhythmic rise and fall of the water at one of our harbors or seaside resorts seems insignificant in comparison.

The fingerprint of the moon is plainly discernible on our tides. The moon rises, on the average, 50.47 minutes later one day than it did the day before; and high tide at a given place occurs, on the average, 50.47 minutes later than the corresponding high water of the preceding day. This precise agreement cannot be a coincidence. Even a difference of a fraction of a second between the two daily retardations would bring the moon and the tides completely out of agreement in the course of years. The moon is therefore the principal cause of the tides.

If one is asked what produces tides, it is not enough to say,

TIDES





PLANETESIMAL HYPOTHESIS

Tidal bulges follow star as it passes, and if torn loose continue to revolve around sun, forming planets.

gravitation. The sun's gravitational attraction for the earth is 178 times as great as the moon's, yet the tides follow the moon. Draw a straight line from the moon completely through the earth, and consider three different chunks of earth-matter intersected by that line, each containing one pound of matter. Let one chunk be at the center of the earth, the other two at opposite sides. All three are attracted towards the moon; but the one nearest the moon is some 4000 miles closer to it than the chunk at the center, and the one at the center is some 4000 miles closer to it than that on the far side of the earth. By the law of gravitation the moon's pulls on the three pieces of matter are different. The pound nearest the moon tends to be pulled away from the center, and the pound at the center tends to be pulled away from the chunk on the far side. The earth is deformed as a result of the moon's different pulls on different parts of it. The portions nearest the moon are heaped up above the average level, and high tide occurs. On the opposite side of the earth a similar heaping up takes place at the same time; there the earth tends to be pulled away from the water, but all we notice is the relative movement, so the result is the same as if the water were being pulled away from the earth.

Thus a given locality experiences, on the average, two high tides in 24 hours 50.47 minutes. The water drawn up to form the high tides lowers the level at intermediate points, hence two low tides occur at a given place in the same period of time. The response of water is not instantaneous: inertia and friction must be overcome. A time-lag results, whose value depends on the depth of the water, the contour of the ocean floor, and the shape of the shore line. For this reason one cannot count on a high tide the instant the moon comes over a given locality. Tide-predicting machines of great size and complexity are used to calculate the tidal data a year in advance.

We see now why the tides follow the moon despite the sun's vastly greater attraction. The sun's pull is more nearly the same on different portions of the earth. To approach 4000 miles nearer to something 239,000 miles away is to be appreciably closer; but to come 4000 miles nearer to an object 93,000,000 miles away is hardly to be closer at all. A sense of proportion, of relative values, must be drawn on here. An overcharge of seven cents on a pound of sugar is robbery, though the same overcharge on the entire Cuban output would scarcely justify calling the police. To put the matter more precisely, a point on the earth nearest the moon is 1.7 per cent closer to it than a point at the center; but in the case of the earth and the sun the corresponding figure is 0.0043 per cent. One must not infer, however, that the sun's effect is negligible. Its attraction is so great that even that small percentage contributes appreciably to the tides. The sun's tide-raising force is approximately 5/11 of the moon's. When the sun and moon are so situated as to be co-operating to produce a high tide at a given place, the total effect is 11/11 plus 5/11, or 16/11 of the moon's effect; when their actions oppose each other the result is 11/11 minus 5/11, or 6/11 of the moon's influence. Thus the maximum tide-raising force is to the minimum as 16 is to 6, approximately, or 8 to 3; and the high tides at the times of new and full moon, when the sun and moon are nearly in line with the earth and hence cooperating, are higher than at the intermediate phases of the moon.

Careful measurements reveal that the solid earth itself yields slightly to the tide-raising force. The earth as a whole is found to possess approximately the same rigidity as steel. By this means we arrive at important conclusions concerning the inaccessible core of our planet.

A Simple Calculation Explodes a Fallacy

Having added tides to our long list of gravitational phenomena, we now consider what role tides may have played in forming the solar system. It is easy to prove that the solar system is not a chance aggregation of bodies. There are nine planets: Mercury,

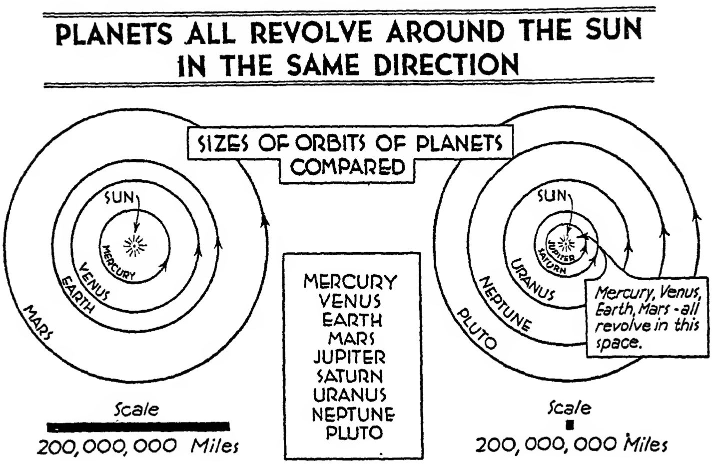


FIGURE 22. Note that the scale is greatly reduced in the drawing of the more distant orbits. For convenience, names of planets should be memorized in the order printed in the central placard. See the *Observer's Guide to the Heavens* at the end of this book for additional information concerning planets and stars.

closest to the sun, then, in order, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto. The planes of their orbits, while not coinciding, are inclined to one another at angles so small that there is only one fairly narrow belt in the heavens, called the zodiac, in which planets ever appear. If we imagine ourselves out in space looking at this belt as one looks at a clock, we see that a planet might traverse its celestial running track in

one of two directions, clockwise or counterclockwise. Yet all the nine planets revolve around the sun in the same direction.

Assume that the direction of a planet's motion is purely a matter of chance. If there were only one planet there would be two possibilities, clockwise or counterclockwise. With two planets there would be twice as many possibilities. Planet #1 can move in either one of two directions, and with each of those motions of #1, Planet #2 may travel either clockwise or counterclockwise—four possible combinations. Add a third planet. With each of those four combinations Planet #3 can revolve either clockwise or counterclockwise, so there are now eight possible combinations. With four planets there are 16 possibilities, with 5 planets 32, with 6 planets 64, with 7 planets 128, with 8 planets 256, with 9 planets 512. There are 512 possible combinations of motion of 9 planets, and if chance were the arbiter the odds would be 511 to 1 against them all going around the sun in the direction they follow.

But this is a small part of the truth. Besides the nine principal planets there are enough minor planets, called asteroids or planetoids, to bring the total number to at least 1273, by a recent count. And they *all* revolve around the sun in the same direction! By this we do not mean that their orbits fit perfectly, one within another, but that if an observer stood off to one side of the solar system he would observe all the revolutionary motion (except for three moons, which can be accounted for) to be taking place in the same general sense, either clockwise or counterclockwise, depending on the point of view. By the time one has multiplied 2 by itself 1273 times he has arrived at a number that would require four minutes to write. It begins with 16 and has 382 additional figures before one comes to the decimal point. To recite it one would need to say trillions 32 times—trillions of trillions of trillions, and so on.

Figure 23. Rim of the sun, showing active solar prominence rising 140,000 miles. The small round disk represents the earth on the same scale. (Photographed at Mount Wilson Observatory.)

With the odds all those trillions of trillions to 1 against them, it is impossible to believe that the 1273 planets and planetoids merely happened to travel around the sun in the same direction. If the reader of this page could set out on a non-stop flight around the world, flying blind, going around the world in all directions over and over again, flying for months, and finally land without warning anywhere at random — in Australia, Greenland, Palestine, Chicago, or Addis Ababa — one would hardly risk a large sum that the first person the flier would meet after landing would be the mayor of his home town. Yet he would have one chance in two billion of doing it, odds so much better than those planetary odds that it would seem like a certainty in comparison.

Failure of the Nebular Hypothesis

To accept the chance theory of the regularity of the solar system in the face of those appalling odds would be to deny the possibility of all knowledge. And if the system did not happen by chance, it was formed. The planets and planetoids were made. Regarding the process of formation we cannot speak so surely. The nebular hypothesis supposed, as we have seen, that the sun was originally a slowly rotating gaseous nebula which contracted and rotated faster, leaving behind at intervals rings of matter which condensed to form the planets. This hypothesis accounts for the fact that the planets all revolve in the same direction as that in which the sun spins on its axis; but if the planets had been formed by such a means each would have retained only a small share of the total quantity of motion, or angular momentum, of the system. The hypothesis falls to the ground because the planets possess nearly all (97%) of the total angular momentum of the solar system although their total mass is insignificant (a tenth of one per cent) in

comparison with that of the sun. For this and other reasons a theory of gradual evolution must be abandoned in favor of a catastrophic action which formed the planets by violence and gave them their great angular momentum at the expense of a body *outside the solar system.*

The Birth of the Planets

In 1900, to meet these requirements, two American scientists, T. C. Chamberlin and F. R. Moulton, proposed the planetesimal hypothesis. The sun and other stars in the universe are known to be moving through space at high speeds. Occasionally two stars must pass near each other. Novae, the so-called new stars which sometimes flash out in the heavens (five brilliant ones since the beginning of the present century) may in some cases be the result of collisions, though the star-population of space would need to be vastly denser than at present believed if collisions were to account for many of the novae.

Picture, then, two stars approaching each other, one of them being our sun. Two huge tidal bulges appear on the sun. The bulges grow larger, they move around the sun as the visiting star sweeps on in its path, until at the moment of closest approach the tidal strain becomes so great that the bulging matter separates from the sun. Internal eruptive forces of the sort that today produce the solar prominences aid in the separation. Some of the matter thus drawn away from its parent body falls back, pelting the sun at an angle and setting it into a slow rotation in the same sense as that in which the tidal bulges had been moving; some, permanently divorced, continues the revolving motion which the passing star had caused. The larger nuclei sweep up lesser fragments by gravitational attraction, gradually building up the major

Figure 24. A spiral nebula (N.G.C. 6946)—one of many exterior galaxies so remote that, if viewed from one of them with a telescope, our own galaxy, including the Milky Way and all within, might itself appear as a spiral nebula. (Photographed at Mount Wilson Observatory.)

planets and their moons; the remainder form comets, planetoids, meteors. Meanwhile the passing star rushes on into space, slightly deflected from its original path and itself the victim of tidal action though not necessarily the mother of a planet family the twin of ours; until today, several billion years after the event, the guilty star, its identity unknown, twinkles back at us from a point at least several thousand times as far as the nearest star.

Thus, in brief, the majestic concepts of the planetesimal hypothesis. For a short statement of the evidence supporting this view one cannot do better than consult the appropriate sections of the text of general astronomy written by one of the co-authors of the theory, Dr. Moulton. Somewhere out there in space, if the planetesimal hypothesis is true, is the star that stood by when the sun gave birth to the planets. We know that the solar system was formed; we know that tidal action could form it; we know by the distribution of the stars and their motions that once in approximately a million billion years a sufficiently close approach of two stars must occur. Is man alone in the universe? It would be far less reasonable to regard our system as unique than to accept the probability that the heavens contain at least a few families of planets resembling ours. Who can say whether intelligent life has developed there? Our study of gravitation, which has led us through so varied an array of related phenomena, has brought us in the end to a seemingly unanswerable question.

OTHER MATERIAL IN THIS BOOK RELATED TO THE UNIT JUST COMPLETED

Observer's Guide to the Heavens — See end of book. An astronomical supplement for the amateur observer. Note especially the articles on Mars, Jupiter and Saturn; the simple method of identifying the brighter stars; data concerning eclipses, meteors, double

stars; and the hints on what to look for in the heavens when observing with small instruments.

SEASONS AND THE WEATHER — Chapter 15
HISTORY OF THE EARTH — Chapter 17
RADIOACTIVITY — Chapter 10
TIME; SPACE; THE UNIVERSE AS A WHOLE — Chapter 18

MATERIAL FOR REVIEW, GROUP-DISCUSSIONS AND SELF-QUIZZING

TRUE-FALSE REVIEW — Appendix, Part 1

SUGGESTIONS FOR SUPPLEMENTARY READING AND REFERENCE

Introduction to Astronomy — R. H. Baker (Van Nostrand)
Consider the Heavens — F. R. Moulton (Doubleday, Doran)
Through Space and Time — Sir James Jeans (Macmillan)
A History of Science — Sir William Dampier (Macmillan)
Astronomy — F. R. Moulton (Macmillan)
From Galileo to Cosmic Rays — H. B. Lemon (University of Chicago Press)
Monthly Evening Sky Map (Magazine) — Celestial Map Publishing Co., 244 Adams St., Brooklyn, N. Y.
The Sky (Magazine) — American Museum of Natural History, 79th St. and Central Park West, New York City

UNIT 2

THE NATURE OF MATTER AND ENERGY

Chapter 5

A BACKGROUND FOR ENERGY

We have now to trace in outline the discovery and applications of the most fundamental principle of nature that physical science has yet brought to light. In the preceding unit we considered some erroneous ideas which were held prior to Newton's discovery of the law of gravitation, and we saw how his splendid flight of genius swept into one unified logical structure a rich array of facts and phenomena whose relations had not hitherto been suspected. Let us now deal similarly with energy.

Conservation Is Fundamental

How fundamental a principle is may be judged by the extent of its applications. A law which applies in many fields, and from which numerous other principles follow as necessary consequences, is obviously more fundamental than one of limited application, such as the law of floating or the law of the lever. By this test, the principle of conservation of energy ranks first. It applies to electricity, light, heat, mechanics, sound, chemical reactions, biological metabolism, and all other physical phenomena. It holds, so far as we can tell, within living matter and in the farthest star. It is at once general and mathematically exact. In recent years the law has swallowed up the principle of conservation of matter, according to which all the products of a chemical reaction, say the combustion of a candle, have the same aggregate mass as the original ingredients. Conservation of matter now appears to be not entirely true

unless viewed as a special case of the broader principle of conservation of energy.

The law itself sounds quite simple: Energy can neither be created nor destroyed. Many of the varied physical phenomena which nature presents to our eyes are merely the outward signs of quantities of energy being changed from one form to another. When the changes occur within a closed system, there is no alteration of the total amount of energy. In other words, so far as energy is concerned, we do not get something for nothing.

A clear grasp of all that is implied by so sweeping a generalization affords great satisfaction to the philosophical mind, which seeks to understand the mainsprings of the universe; and in practical matters, as we shall see, the knowledge provides a tool of great power which man can use in his efforts to mould his environment more nearly to his will. The history of thought shows time and again the danger of dogmatic assertions; yet in the present state of knowledge it seems that if man is to discover a more fundamental law it must needs be one which bridges the gap between physical actions on the one hand, and on the other, the apparent spontaneity of certain phenomena of living matter and the complexities of the mental reactions with which psychology has recently begun to wrestle.

What Is Energy?

The law is not as simple as it sounds. What is energy? Energy is sometimes defined as the capacity for doing work. But what is work? Is work to be defined as that which makes one tired? Decidedly no: a person can become very tired without doing any work in the physical sense other than that which his bodily organs automatically perform in keeping him alive. He may grow weary

as a result of supporting a suitcase without doing any work on it, or by sitting too long beside a boring dinner companion. These matters cannot be dismissed in a moment. Another definition of energy is that it is anything which can be transformed into heat.

Our statements may seem abstract and evasive. How is one to define something which seems to be more fundamental than anything else in physical nature? The physicist has had to learn to deal with abstractions. Without ever giving up the sure ground of experiment he has become a philosopher in spite of himself. Experimental researches have led him far beneath the outward show of external appearances. So far has he gone into those precincts of metaphysics which deal with the problem of physical reality that philosophers have well-nigh yielded this portion of their great field. In the original Greek *metaphysics* meant *beyond physics,* but, as someone has remarked, perhaps physics is already there.

Although energy can be measured, it is not directly perceived. We infer its existence from its effects. The kinetic energy of a moving vehicle is put in evidence when a collision occurs. The energy of a stream of electrons may be inferred from its heating effect in a lamp filament. Heat energy reveals itself through hotness, which we can sense directly, or by the melting of ice or other effects. An iceberg contains vastly more heat energy than a cupful of boiling water, yet the touch of the hand gives no evidence of this. The incandescent sun affects our eyes; but what we see is not the luminous energy but the object it comes from. When the plunger of a pile-driver is poised at the top of the shaft, ready to fall and drive the pile into the ground, you may examine it all you wish without finding it to be any different than when resting on the ground. Yet on letting it fall one can tell by seeing the pile driven into the earth like a gigantic nail that energy must have been stored

in the lifted mass, or, as the scientist would say, in the pair of objects, the plunger and the earth.

Despite the intangible quality of energy, it must not be dismissed as unreal. Nowhere does science calculate more accurately than in the field of energy, or predict results more surely. The officials of the United States Patent Office, hard-headed experts all, have learned the lesson of conservation of energy so well that if a cursory examination shows that a proposed machine would violate the law, they reject the application without even bothering to read the details.

The Search for the Unseen

Different ages have different ways of approaching nature, but all approaches since the dawn of history have resembled each other in one respect. The savage twirling his fire-drill; Plato and Aristotle of the Golden Age of Greece; the scientist of today — all have sought an underlying reality behind appearances. From the earliest records of thinking man we find that in all climes and ages he has held an overpowering conviction of the existence of a basic fundamental reality to which daily events and surface phenomena merely provided the clues.

The savage of antiquity saw nearly the same face of nature that we see — clouds, stars, stones, trees, animals, paths in the woods, bodies hurtling to earth, fire springing up under the influence of lightning or artificial friction — and behind that face he saw spirits and demons swarming on every hand, ready either to help him or to encompass his destruction. Before going out to hunt or to face the storm or to vent his hatred in war he had recourse to sacrifice and the weird incantations of magic, but his aim was as intensely practical as that of the modern exponent of applied science. He

wanted to set the scene to ensure success. Conceptual thought was what he lacked, the ability to find the general principles behind particulars.

Plato, greatest philosopher of ancient times, teacher of Aristotle, looked behind the face of nature and found ideas. Here was a mighty step forward, but the ideas were not ideas in our sense of the word. The particulars which we perceive with our senses, said Plato, are not true reality. Conceptual thought alone, he believed, could reveal the essential element in things. The particular objects perceived by our senses were for Plato mere copies, very imperfect copies of the transcendent forms or ideas which alone constituted the true, eternal, unchanging substratum of the universe. Plato disdained experiment. If there had been in his day a scientist devoted to the slow patient accumulation of experimental facts, Plato would have looked on him as one who held his nose so close to the book of the universe that he could not read the print. The noble mind, he said, the mind of the philosopher, looks into the mind of the universe directly, seeing the ultimate truth with a vision unclouded by any blurring screen of facts. The mind he meant was not what we mean by God: it was the sum-total of ideas, all that was real in the universe.

Today the physical scientist looks behind the face of nature and sees something no less mysterious than the savage's demons; but he looks clear-eyed and unafraid, and finds order, an underlying something which is invisible, intangible, yet never arbitrary. He rejects the savage's superstitions; he accepts, whether he realizes it or not, Plato's ideal of conceptual thought; he resolutely ignores Plato's low regard for facts and particulars. The scientist examines nature minutely, makes her stick out her tongue, so to speak, say "Ah" and lie down on the x-ray table—and to the facts gained by these diagnostic experiments he applies conceptual

thinking until he finds what Plato would have called the ideas of the universe, the substratum of reality.

The Relations behind Particulars

An observation which everybody has made shows in a flash how absurd it would be to accept only the immediate particulars presented by one's senses. Standing beside the lapping waters on a dark night one may see on the ruffled surface of the lake a streak of light stretching directly towards him from a lamp on the opposite shore. Everywhere else the water appears inky black. Strolling along the shore, watching the water, one finds that no matter where he stands there is that single streak of light connecting him with the lamp. Where was darkness is now light; where was brightness is now the dark. By the time one has walked the length of the shore, the bright streak seems to have swept the entire surface — but surely the light has not followed the stroller! All the bright streaks remain in place. The whole surface of the water is aglow with light, even where it appears black to the lone observer. The senses give merely the raw materials of thought. Analytical thinking discovers the truth.

A famous physicist has given an interesting analogy. Picture yourself, he said, on the first floor of a building whose upper stories you are forever forbidden to enter. Many ropes hang down through holes in the ceiling of the room where you are. Pulling one rope you find that it yields, as if connected to movable machinery above. At the same time the dangling end of another rope rises, as if in response to the downward pull of the first. Intrigued, you pull one rope after another, find which other ropes rise or fall in response, how the distances of movement compare, how the forces exerted are related. Gradually, inevitably, you

build up a picture of what that unseen mechanism must be to act in accordance with the laws which you have found by pulling the ropes. How many ages man lived in his little room before he thought of pulling a rope! And how far he has progressed once science began to pull them!

What Is Real?

Is the machine that those ropes are fastened to, real? Is energy real? Is gravitation? Are the electrons and protons, positrons and neutrons with which we shall deal, real? Are they abstractions? No one has ever seen the orbit of a planet. Is orbital motion real?

Usually, it is true, the physicist or chemist does not trouble to argue the question. He merely sits down with the law of energy in the back of his head, or whatever law may be appropriate to the problem, considers the ends desired, applies such mathematics — arithmetic, algebra, geometry, trigonometry, calculus, vector analysis — as may be needed, and he rises from his transcendental dealings with abstractions with a number on a piece of paper. Arrange your materials thus and so, he says. Take so many pounds of this, so many of that, mould them into such a shape, apply so many kilowatt-hours of electric energy, or so many calories of heat energy, or such a force at such a place, and the result will be the one given by this number. But do not trust the third decimal, he may add, or the second or the tenth, as the case may be. He gives the result with utter confidence, not even considering whether he has dealt with reality or not; and he points out his probable percentage of error before anyone else can find it.

Suppose we question the validity of his method. "You have dealt with the law of energy," we say, "yet you cannot show us any energy. You have used mathematics until your notes look

like a maze of hieroglyphics to us. Can you prove that mathematics has an objective reality apart from man's mind?"

The scientist's first answer, invariably, is a laconic "Try it." We do so, as many times as we choose, and the result agrees with the number written in advance on the slip of paper. But we press him harder. "The particular facts are real," we admit, "but the laws seem to be mere relations or abstractions invented by the human mind. The laws are expressed, and in part discovered with the aid of mathematics, and mathematics itself not only rests on axioms which are accepted because they seem *reasonable,* but the development of the whole structure has been determined by our own ideas of logic and consistency. How, then, can you claim to have discovered objective reality?"

The scientist, if he is busy, may be slightly annoyed at this raising of questions, but you can get him to discuss the matter. I grant you, he may say, that there is no hard and fast answer to your question. You may even, if you wish, adopt the most egocentric form of idealism. You may choose to believe that your mind is the only reality, and that this number on the slip of paper, and I myself, and your own body, the trees and mountains, your history books, all the great poems, concertos, scientific discoveries and other flights of genius that you read about, everything that you observe, are the idealistic creations of your own mind. This seems unduly flattering, but believe it if you choose. Second, you may suppose that the universe is filled with a chaos including every imaginable possibility, of which man can perceive only those elements which agree with his conception of reasonableness and consistency. It would appear difficult to explain, by that view, the numerous instances of discoveries which did not seem reasonable when made, and a few known facts which have not even yet been fitted into a logical frame. Third, you may believe that thinking

itself, including mathematics, is experimental, determined by material reality, in which case our scientific abstractions and mathematical conclusions would naturally agree with observed results.

"There are other explanations of the apparent agreement between mathematical thinking and objective reality," he concludes, "at least one of which would carry us deep into religion; but all the scientist can *prove* is that science works, and I am not going to doubt the surest road to knowledge that is independent of opinion that mankind has yet discovered. It is true that science deals primarily with experience, and then reasons from that experience to the nature of an underlying reality; but if one calls that second step a mere inference how can he explain the fact that the picture of basic physical reality thus arrived at has so often led to the successful prediction of new experiences or observations never before reported? Can the underlying reality cancel out in all such cases? I do not attempt an all-inclusive definition of what is real — but I am convinced that any philosophy which fails to take into account the facts revealed by physical science will prove inadequate. Now won't you please go over to the philosophy department and argue to your heart's content? I have some work to do with energy."

A Thousand Years of Greek Physical Science

The ancient Greeks had no conception of energy. Energy, and conservation of energy, are strictly modern discoveries. But new ideas do not occur in a void: they are related to the intellectual background of the race. Let us see quickly what was known when the great period of Hellenic thought came to an end. Around the shores of the Aegean and the Adriatic, and across the Mediterranean at one of the mouths of the Nile, in Alexandria, arose a

kind of thinking which flowered, at long last, in the science of modern times. The historian divides the period into two: one Greek, one Roman; but the student of science sees only one. Science sprang from a thirst for knowledge, a burning desire to see the universe whole and solve its riddles; and the Romans, an intensely practical people, were indifferent to abstract thought. What science they had was Greek.

If, for convenience, we choose an even thousand-year period from the earliest precisely known date of Greek natural philosophy, we find it exactly spanning the gap from 585 B.C. to 415 A.D. In the latter year Hypatia, the last astronomer and mathematician of ancient Alexandria, brilliant and reputedly beautiful daughter of Theon, was torn to pieces by a mob; and in the first year of our chosen epoch, on May 28, occurred an eclipse which had been predicted by Thales of Miletus, the first thinker recognized by critics as a philosopher, not mythologist, of nature. Thales was probably born about 640 B.C.; but so dim are the records that 585 is the only date in his life that we know. Astronomy, calculating back, finds the date of Thales' eclipse and thus comes to the aid of history. Thales seems to have been the discoverer of electrification of amber by friction; he knew of the magnetic attraction of the lodestone; he predicted the eclipse with accuracy; he saw in water the primary element of all matter, and in all the things of nature he saw life and demons. A small start, one may say, for philosophy of nature — but science crawled before it walked, and it walked for long ages before it burst into the run of modern times.

The end of the epoch might easily be set a century or two earlier, for Hypatia was at best one of the last bright gleams in a depressing picture that was several centuries in the painting; or we might go forward another century to Boethius, the last Roman philosopher of antiquity, who left texts of astronomy, geometry, music and

arithmetic to float on the black tide of ignorance when the Dark Ages, already begun, engulfed his civilization. The Western Empire was a long time rotting, and the barbaric though vigorous Teutons who took the helm when the Roman hand slipped listlessly from the wheel were not the ones to foster learning.

The thousand years are studded with names known to all who are interested in the history of culture. Pericles, Alexander the Great, the Pharaohs Ptolemy, Julius Caesar, Cleopatra, the Emperor Augustus and Constantine the Great made their names in the field of government and war. Aeschylus, Phidias, Herodotus, Euripides, Sophocles, Thucydides, Aristophanes, Cicero, Horace, Vergil, Plutarch and Pliny enriched art, literature, history. In philosophy and science we find Socrates, Plato, Aristotle, Euclid, Archimedes, Claudius Ptolemy and many others. Gautama, called the Buddha; Confucius; Jesus of Nazareth founded religions. Stirring times they were, great times, loaded with a freight of thought and action that has had tremendous influence in shaping the world we live in. Yet how long ago it all seems! The Jutes, Angles and Saxons, Teutonic tribes, were invading and settling Britain at about the time when Hypatia's sufferings were bringing our chosen epoch to an end.

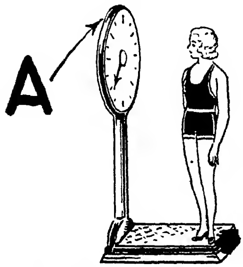
A thousand years is a long time. How much of true science was known when the period was over? Three exact laws of nature; two surprisingly far-sighted and fertile guesses; a mass of astronomical information; and a great many useful but isolated facts, notably in chemistry, whose relations were not understood. All the exact laws lay in the field of physics: two in mechanics, one in light. It will not take long to summarize these gleanings of a thousand years of genius.

Archimedes' Principle of Buoyancy

Here is a law on whose truth millions of dollars are staked unquestioningly every time a new ocean liner is launched. Any body immersed in any liquid is buoyed up by a force equal to the weight of the liquid displaced. A simple statement, yet powerful because general and exact. When the huge Normandie slipped into the water it settled precisely to the water-line carefully determined in advance with the aid of Archimedes' principle. Archimedes lived about 287–212 B.C., in Syracuse, Sicily, but spent much time in Alexandria. The problem of detecting adulteration of gold with silver in a crown intended for Hiero, King of Syracuse, is supposed to have led him to this great discovery. By suspending the crown in water and weighing it, then repeating the experiment with equal weights of gold and silver, Archimedes readily measured the percentages of gold and silver by comparing the apparent losses of weight, due to buoyancy, and applying his law. An interesting variation of this experiment can be used to determine the average density of the human body. With an object in the hand to ensure complete immersion, let yourself be weighed with a spring balance while suspended in the water under the diving board. As one practical conclusion from the law, one sees the folly of any frantic waving of arms in the air when in trouble in deep water: let them displace water and help buoy you up.

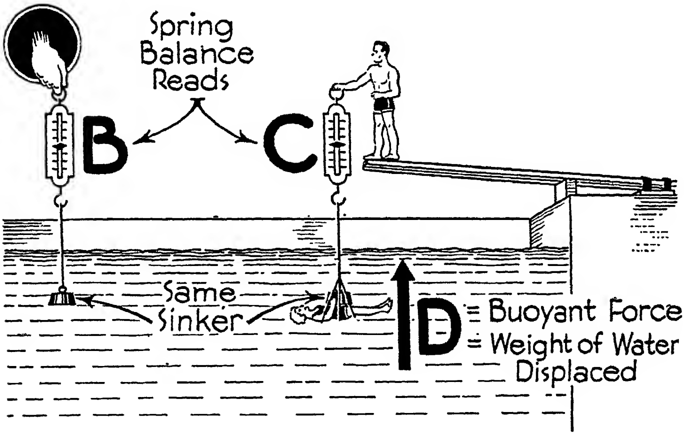
The concept of density, or mass per unit volume, was implied in Archimedes' work, also the principle of center of gravity. Archimedes did not extend his law to gases, but it applies to immersion in any fluid, whether liquid or gaseous, and whether sinking or floating occurs. It is as useful in designing gas-filled airships to float in the atmosphere as in designing ocean liners that will sink to a pre-determined water-line, or pontoons to raise sunken ships.

22 CENTURIES AFTER ARCHIMEDES



TEST YOUR OWN BODY BY HIS PRINCIPLE

$$\underset{A\,+\,B}{\text{Forces Down}} = \underset{C\,+\,D}{\text{Forces Up}}$$



EXAMPLES:	A + B − C = D	SPECIFIC GRAVITY = A ÷ D	
John Doe	150 + 10 − 20 = 140	1.07	*He Sinks.*
Jane Doe	130 + 10 − 5 = 135	.96	*She Floats.*

IF YOUR SPECIFIC GRAVITY IS LESS THAN 1.00 YOU FLOAT WITHOUT EFFORT

FIGURE 25. An easy experiment. The spring balance should be tested with accurate weights beforehand, and any errors allowed for. If the subject exhales just before coming up, the effect of a chestful of air can be measured.

The Law of the Lever

Here is another exact law discovered by Archimedes. Civilization owes much to any person who first states clearly a principle which can be applied to overcome great resistances with ease. After that, man works in the light, surely and accurately, not by rough rule-of-thumb. A small force on the long arm of a lever can produce as great a turning effect as a large force on the short arm. Archimedes discovered that the turning effect is proportional to the length of the lever arm, which is the perpendicular distance between the point of application of the force and the axis about which rotation is to occur. Archimedes did not define the lever arm precisely, but the principle seems to have been very clear in his mind. The turning effect of a force (its moment) is equal to the product of the force times the lever arm. Because of this principle of nature we put long or large handles on things that we want to turn with ease. The simplest applications are perhaps the crowbar, the burglar's jimmy, the doorknob, automobile steering wheels, and the beam balance or steelyard. The law is applied daily in designing the complicated modern mechanisms of levers and gear wheels which work such wonders in overcoming huge forces at the expense of small ones. But in terms of energy and work, as we shall see, we do not get something for nothing, despite the ease of the effort.

The Law of Reflection of Light

Who first discovered this law is not known, but it seems to have been common knowledge among the learned rather early in the period. A beam of light striking a smooth surface is reflected off in such a direction that the reflected beam and the original (or

incident) beam make equal angles with the perpendicular to the reflecting surface at the point of incidence. Thus light is reflected just as a tennis ball striking a wall would be if the ball and the wall were perfectly elastic. An ivory ball striking a steel anvil nearly meets the requirements. With the aid of this law of reflection the image-producing performance of mirrors, both flat and curved, can be accurately deduced, but the Greeks did not go that far, though they used mirrors of both sorts.

Knowledge of Astronomy and Light

These three discoveries were the period's contribution to our knowledge of exact and general laws of nature. In addition, much statistical information concerning the locations of stars, planets and the moon was amassed; the length of the year was determined to within 374 seconds of the modern value; the earth's roundness was established by latitude and longitude measurements, and the slow wobbling of its axis detected. The true idea that the earth revolves around the sun was proposed by Aristarchus, but firmly rejected on the overwhelming authority of Hipparchus, inventor of trigonometry, and of Claudius Ptolemy.

Some measurements of the bending of light when it entered water were made, and burning glasses were employed in supposedly spectacular demonstrations; but the *law* of refraction was not known. The fact that light travels in straight lines was accepted; but despite the evidence of shadows and of images in still water a most extraordinary hypothesis of ocular beams, an emission *from the eyes* of " the pure fire that is within us," was advanced in an attempt to account for vision. Here there was no clarity at all. An external source of light was recognized as a necessity, yet vision was supposed to result from messengers sent out from the

eye to report on the object seen. Plato gives a typical explanation in the *Dialogues* (Timaeus).

Developments in Chemistry

No *laws* of chemistry or of heat were known; but glass, an Egyptian discovery, had been manufactured for at least two thousand years by the time this period closes; and the records mention seven magic metals — gold, silver, copper, iron, lead, tin, quicksilver — hence heat and many chemical reactions, though not understood, must have been put to excellent use in processing materials. These seven metals, together with sulphur and carbon, comprised the nine chemical elements which were known to the ancients in elementary form. The discovery of these is shrouded in the mists of prehistoric time.

Many chemical compounds were also known, though by no means recognized as such. Lead carbonate, for example — the white lead of the modern house-painter — was called *cerussa* by Pliny; its formation by the action of vinegar fumes on lead in the presence of air was well known as early as three centuries B.C. Indeed, chemistry as an art or craft, not a science, was already several thousand years old. The great antiquity of embalming is well known. For many centuries the Egyptians and other Mediterranean peoples had been dyeing goods; tanning leather; extracting medicines from plants; glazing pottery; producing alcoholic drinks by fermentation; winning metals from ores, refining and alloying them. So successful were these early metal-workers in producing alloys which looked like gold or silver that in about 292 A.D. the Roman emperor Diocletian commanded all books on *chemia* to be destroyed. Diocletian's attempt to protect either his currency or his subjects (we do not know which) from the debas-

ing effects of fraud and counterfeiting signalizes the beginnings of *alchemy,* the first distinct school of thought in this field and the forerunner of chemistry proper. Beginning with practical and entirely legitimate attempts to make cheap imitations of costly substances, these advance agents of chemistry gradually came to be obsessed with the philosophical idea that gold was the eternal and highest principle of all metals. Thus was born the branch of knowledge whose prime aim for centuries was to be the discovery of the philosopher's stone, a magic substance which by touch would transmute base metals into gold.

Zosimos of Egypt, who studied as a youth in Alexandria at about the time of Diocletian's reign, is the earliest alchemical author yet identified by apparently genuine writings. Zosimos believed in transmutation; he mingled sound chemical recipes with bizarre fictions; and either he first, in his writings, or Diocletian in his decree, seems to have given chemistry its name. In token of the black soil of the Nile, Egypt was early called *Chemi.* Hence *chemia,* the Art of Egypt, or, as medieval writers, with more than a hint of justice, were soon calling it, the Black Art. A second derivation, based on a corruption of the Greek for *liquid,* seems possible but less likely.

Other Physical Knowledge of the Greeks

Two forces of attraction, electric and magnetic, had been noticed, restricted to amber and lodestones; there was no understanding whatsoever of these effects. A shrewd guess that matter is composed of moving atoms was advanced, foreshadowing modern views. Hero of Alexandria applied the expansion of air heated by the altar fire to force water into a hollow counterpoise which was connected by pulleys to the temple doors; when the counterpoise

became sufficiently weighted with water, the temple doors opened automatically. He also made rotating toys driven by the reactive forces of steam jets, resembling our rotating lawn sprinklers; and is credited with the invention of the force pump and the siphon.

Views of motion may be inferred from our earlier discussion of Aristotle; but we should add another of his erroneous ideas. A missile thrown through the air continued in motion because the air displaced at the front went around behind and pushed!

Despite many errors, the contributions of the period are really amazing when one considers that only length, weight, angles, and long intervals of time could be measured accurately. For short intervals of time, there was no clock better than the dripping water clock, or clepsydra. The first mechanical clocks, driven by weights or springs, were not invented until 1360—and even these were so inaccurate that they were provided with hour hands only, no minute or second hands. The first accurate time-measuring device was Huygens' pendulum clock, which resulted immediately from Huygens' discovery of the law of the pendulum in 1657, more than a thousand years after the close of the thousand-year period with which we are dealing. And the basic thermal quantity, temperature or hotness, on whose accurate measurement all exact knowledge of heat energy must rest, was never measured accurately until 1714, when Fahrenheit invented the scale with which every householder is familiar. Even rough estimates of temperature changes were not possible until Galileo invented a crude indicator operated by the expansion of air.

In the field of sound, the Pythagoreans contributed several facts, including the discovery that halving the length of a taut string raises the pitch of its fundamental note by one octave.

Evaluating the Period

Concluding our brief and inadequate summary of a great period, we must assess the scientific and analytical accomplishments of the Greeks as greatest in philosophy, mathematics, physics, and astronomy, and probably in that order. Philosophy gave man a new point of view and made the remainder possible. Mathematics made spectacular advances: the geometry of Euclid; the trigonometry of Hipparchus; the algebra of Diophantus; the close approach to integration, one of the operations of the calculus, of Archimedes.

Psychology, as we understand the word, did not exist. There was some knowledge of anatomy. Ideas of physiology were crude and, in a large measure, erroneous. A mass of biological observations was assembled and partially classified. Anaximander suggested a crude form of evolution, guessing that man, and every animal, rose in the beginning from the sea, a fish. Aristotle practised dissection. This man, who made so many mistakes in physics, did much better, relative to the present status of the two studies, in biology; but no exact and general laws of living matter, in the sense in which physics uses the word, were known, and few are known today. But though Archimedes' laws of buoyancy and the lever are exact and general, who will balance them, for importance, against our fragmentary present knowledge of the biological actions of vitamins? or all of those together against even a few accurate glimpses into the creative imagination if we could only get some? We must get used to the idea that the sciences which deal with living matter are to flower later than the physical sciences. Just as physics requires the fruits of the mathematician's labors, so the sciences of living matter have waited on the instruments, methods, and concepts of physics and chemistry. Animate matter, especially that which itself tries to find the laws of all, seems

to be harder to deal with, apart from qualitative description, than inanimate matter. If some future generation should find itself in possession of an organized system of exact and general laws of living matter, including the human brain, what may not prove possible?

But we digress. Let us award the thousand-year palm, quite tentatively, to Plato and Archimedes — and now for a quick flight through another thousand years.

Another Thousand Years

We pass now to a dismal prospect. The first thousand-year period of our convenient though arbitrary division of history carried us from the dawn of philosophy and science to the murder of the last mathematician and astronomer of ancient Alexandria, in 415 A.D. Another thousand years brings us nearly to the birth date (1452) of that versatile genius of the Italian Renaissance, Leonardo da Vinci. Thus we are now bridging the gulf between ancient learning and the succession of men — Leonardo, Copernicus, Tycho Brahe, Kepler, Galileo — whose achievements were considered, in part, in an earlier chapter. If the Greeks, who started, perforce, so nearly from scratch, could write the magnificent chapter of thought which we have so briefly summarized in the preceding pages, who would venture to set any limits to what might reasonably be expected of the thinkers of the next thousand years?

What did they do with their heritage? The Greeks bequeathed them an open mind, confidence in reason, a curiosity that dared to face the universe, a splendid equipment of mathematical tools, the concept of natural law, and a body of knowledge which, despite numerous errors, included, as one item, three exact and general laws of nature. The answer to our question can be suggested by

two revealing facts. Though Zosimos, for one, had left many chemical recipes and voluminous descriptions of chemical manipulations, this thousand-year period contributed only one new element (arsenic) of all the 83 that remained to be added to the Greeks' nine. Here we follow Professor Harrison Hale's recent revision. And — as our second revealing fact — all these ten centuries did not add a single exact law to man's knowledge of nature. Hipparchus and Ptolemy, between them, left a well-developed trigonometry and accurate measurements of the refraction of light in water for every ten degrees, yet the two were not put together to discover the simple law of refraction until two centuries after the close of this thousand-year era. Yet optics and alchemy were two of the fields in which the Arabians specialized in this, their greatest period.

How shall one explain the appalling breakdown of science in Europe after so fair a start? Snap judgments are usually misleading. Those people were our ancestors. Great minds existed. The laws of heredity, still so imperfectly known, were operating. Good stock was doubtless producing good stock, at least about as often as it does today. Let us remind ourselves which period of history it is with which we are dealing.

In 410 A.D., five years before our arbitrary opening date, Alaric the Goth captured Rome. Odoacer did it again in 476 — a mere formality — and the fall of the Roman Empire, long a fact, was officially recognized in Constantinople. In 529 Justinian I, ruling in Constantinople as emperor of the Byzantine portion of the Roman Empire, closed the University of Athens in an attempt to further Christianity. In 544 Saint Benedict died, leaving behind him the beginnings of the famous order which through the Dark Ages provided sanctuary in its monasteries for many priceless manuscripts. Mohammed was born twenty-six years later; be-

fore he died he founded a religion whose vigorous followers, spreading the Moslem rule in one century through Asia Minor, North Africa and Spain, initiated a movement to which medicine, mathematics and science owe a debt. In 590 Pope Gregory the Great began to rule in Rome as an independent king; and for long centuries now the pope was to claim, and sometimes exercise, supreme power in Europe, both temporal and ecclesiastical. In 732 Charles Martel, ruler of the Franks, stopped the Moslems at Tours and thus held the Mohammedan invasion south of the Pyrenees. Pope Leo III crowned Charlemagne emperor of the new Holy Roman Empire on Christmas day in the year 800. Pope Urban II summoned the first crusade against the Mohammedans in 1095, and not until 1270 did these expenditures of life and energy cease, when Louis IX, King of France, died of fever in Tunis while leading the eighth and last crusade. In the meantime, in 1215, the liberty-loving Englishmen wrested Magna Charta from King John. The superb cathedral of Notre Dame — a vision in stone and glass — was begun in 1163; the cathedral of Chartres was dedicated in 1260.

Passing rapidly over several names which will help to place the closing centuries — Genghis Khan, the conqueror from Asia; Thomas Aquinas, Roger Bacon, Dante, Marco Polo, Petrarch — we come to the end of our thousand-year period and find it marked off exactly by the death of John Huss, the learned rector of the University of Prague, who was burned alive in 1415 on a charge of heresy.

Authority and Salvage the Keynotes

The thousand-year epoch from 415 to 1415 both begins and ends with the cruel death of a distinguished scholar. If *free enquiry* and

intellectual progress be taken as the watchwords of the first thousand years, *authority* and *salvage* may be adopted as the keynotes of the second. The greatest service the Middle Ages rendered science was to uncover and transmit the knowledge of the Greeks after the records had been all but lost in the turmoil which followed the dissolution of the Western Roman Empire. It was an age of social, political and economic upheaval in western Europe. Amidst war, poverty, plagues of disease, the rise of nationalism, the labors of establishing and extending the influence of a powerful church, and the painful progress of great masses from slavery through serfdom to a state remotely resembling freedom, science was largely neglected. Eyes were lifted to Heaven, and there was no lack of authoritative voices to keep men terribly aware of Hell. Reason became the servant of faith. Several centuries later, the stubborn refusal of educated men to believe what Galileo's telescope showed them bore eloquent testimony to the thoroughness with which the habit of relying on authority had been inculcated. To pass judgment on the period would be to judge mankind. Institutions may make men, but man makes the institutions.

Scientific Contributions of the Period

The period's contributions to physical science can be summarized very briefly. Chemistry was chiefly alchemy, and was marked by the search for the philosopher's magic stone, which supposedly would transmute the cheaper metals into gold, and for the elixir of life, a magic brew intended to cure all human ills. Jabir-ibn-Hayyan, Arabian alchemist known later as Geber, was welcomed in Bagdad by the renowned calif Haroun al-Rashid in the eighth century. Geber discovered nitric acid, left recipes for inks and dyes, and attempted to explain the nature of metals by regarding

them all as products of sulphur and mercury united in different proportions. A little later Albatenius, principal Arabian astronomer, reduced Hipparchus' error in the length of the year by more than half: from 374 seconds to 144. About 900 A.D. the Persian alchemist Razi introduced the idea of systematic classification of chemical substances and reactions. Alhazen, Arabian physicist, discarded the old incorrect hypothesis of ocular beams, increased our knowledge of the eye, and made minor advances in the study of reflection and refraction of light. The alchemists' belief that base metals could be transmuted into gold was combated, with little success, by the Persian physician and chemist Avicenna, who was born about 980. Albertus Magnus of Bavaria, Dominican monk, probably isolated arsenic about 1250; and Roger Bacon the Englishman, a contemporary Franciscan friar, though accepting the false ideas of alchemy and astrology, forcefully advocated greater emphasis on both mathematics and experimentation in the study of nature and stressed the possibilities inherent in chemistry as a science in itself rather than a mere craft to aid the practical arts.

Probably the principal contributions of the Arabian scholars were indirect: they translated many of the Greek writings, and they introduced into western Europe the so-called Arabic decimal system of numbers (actually of Hindoo origin). Decimal fractions came much later, but in replacing the clumsy Roman notation with the whole-number portion of our present convenient system of writing numbers the Arabian school rendered Europe a genuine service. There were also improvements in algebra. Crude spectacles came into use at about the end of the thirteenth century, but for good lenses man must await a better knowledge of the physics of light. Artificial magnets made by stroking iron with natural lodestones appeared in Europe in 1190 and were used as mariners' compasses.

So far as Europe is concerned, the historian of the art of medicine might possibly speak a little more optimistically of the period; but modern medicine could not arise except on a sound foundation of chemistry, biology, and physics.

To the student of science, this fascinating period presents chiefly a weird mixture of superstition, alchemy, astrology — an age in quest of magic. Let us hasten on in our search for energy. What was man to accomplish now in science, with two thousand years of experience under his belt? We cannot head our next section *Another Thousand Years,* for 522 years bring us to the year 1937, and who would predict what the coming half-millenium of the future holds in store?

The Transition to Modern Science

We seem to be making slow progress towards conservation of energy; but so sweeping is the principle, so broad the outlook which it implies, that in a philosophical sense every step in the advance from mythology to energy is relevant mileage along the devious highway of preparation. The five centuries left over after our even two thousand years form a period in which, after a leisurely start, important and often spectacular developments occur in so swift a succession that never again does science lapse into the slow pace of the first twenty centuries. A few familiar names and events, some of which have already been considered at length in our pages, will give a quick bird's-eye picture of the western world as it yawned, stretched, and finally, as the scientist sees it, became wide awake and ready to go.

Leonardo da Vinci, the first man to voice the modern point of view in science with reasonable clarity and conviction, was born in Italy in 1452. A year later the Turks, a people so different in culture from their brother Mohammedans who had promoted

scientific progress during the Middle Ages, conquered Christian Constantinople, and many scholars, fleeing from Turkish barbarities, hastened to western Europe with their manuscripts. Johann Thölder, Dominican monk who wrote under the name Basil Valentine, isolated antimony about 1450. Johannes Gutenberg died in 1468, leaving the art of printing with movable type well established in Germany. Michelangelo was born in 1475, Raphael and Martin Luther in 1483, Benvenuto Cellini in 1500.

In the year 1492, in a memorable campaign celebrated in the writings of Washington Irving, Queen Isabella and Ferdinand, patrons of Christopher Columbus, ended the eight-century rule of Mohammedans in the Spanish peninsula by capturing Granada, the last Moorish stronghold in Spain. Copernicus published his monumental work on the solar system in 1543. Two years earlier, Paracelsus, father of medical chemistry, had lost his life at the hands of the servants of an enraged physician — violent end of a tempestuous but useful life; and about this time Georgius Agricola, founder of scientific metallurgy, published *De Re Metallica,* which remained the authoritative text for several centuries. Shakespeare was born in 1564. Intolerance was in the air: Sir William Dampier estimates that nearly a million persons were executed for witchcraft in the two centuries beginning about 1484.

In 1588, at a time when Spain was firmly entrenched in America from Florida and the Californias south, the English fleet destroyed the famous Spanish Armada, thus opening the way to English colonizers in America. In 1590 Galileo crystallized the growing opposition to Aristotelian science by performing his famous falling body experiment, and ten years later Sir William Gilbert, Queen Elizabeth's physician, published the first scientific treatise on magnetism. In 1607 and 1620 the defeat of the Spanish Armada bore fruit in the founding of Jamestown and Plymouth, respectively,

John Kepler completed his laws of planetary motion in 1618, and ten years later William Harvey described the circulation of the blood. In 1643 Louis XIV, *le Roi Soleil* of France, began his glamorous seventy-two-year reign. In 1661 Robert Boyle, Irish-born physicist and chemist of Oxford University, distinguished accurately between chemical elements and compounds, and thus cleared away the alchemical underbrush which for many centuries had been smothering the young shoots of chemistry as fast as they sprouted in the soil of genius.

Olaf Römer, a Danish astronomer, measured the velocity of light for the first time in history in 1676, using an ingenious deduction from apparent inconsistencies which he had discovered in the motions of Jupiter's moons — a far cry from the ancient idea of ocular beams! Isaac Newton published his epoch-making treatise, the *Principia,* in 1687, and modern science was on its feet, never to stagger again though destined still to make numerous errors of hypothesis.

So we reach the beginnings of the modern age of science without finding the answers to the questions which we raised at the beginning of the chapter. After surveying more than two thousand years of scientific thought we have not found energy, we have not found conservation of energy, we know little more than we did at the start of the underlying nature of physical reality. But we have laid an historical and philosophical foundation from which to take off in quest of ideas so significant, so revolutionary in their influence on our conceptions of ourselves and of the universe in which we dwell, that we may well make a fresh start in a new chapter.

Chapter 6

CONSERVATION OF ENERGY

By the time Galileo died, science had begun to advance on many fronts. Among the most important of the movements was that which led eventually to the measurement of temperature. Heat is central in the development of the modern doctrine of energy, and no progress whatever could be made towards exact knowledge of heat until temperature or hotness, the basic thermal quantity, could be accurately measured.

Measurement of Temperature

Galileo himself invented the first device to indicate changes of temperature. Like the household thermometer of today, it depended on expansion for its action, but air was the expanding material, not mercury. If one will take a hollow glass globe with a long hollow stem, warm the globe to expel some of the air by expansion, then mount it upright with the open end of the stem immersed in water or other liquid, he will have a simple thermoscope similar to Galileo's. As the air cools to its former temperature, its pressure will diminish, and atmospheric pressure on the surface of the liquid in the dish will push liquid up into the stem. After that, any cooling or warming of the air in the bulb will be indicated by the rise or fall of the column of liquid in the stem. Accounts of Hero's application of the expansion of air in Alexandria may possibly have suggested the idea to Galileo. Unfortunately, Galileo's instrument had no accurate scale, and was also,

quite unintentionally, a crude barometer as well, since changes of atmospheric pressure would also raise or lower the indicating column.

Improvements, however, came rapidly. Within seventeen years after Galileo died a French astronomer named Ismaël Boulliau had made a better indicator by sealing mercury in glass, and Italians of the short-lived Florentine Academy used a similar construction, though not mercury, which is especially suitable because of its low freezing point, high boiling point, and its negligible evaporation at ordinary temperatures.

But still no scale was at hand. Two Englishmen, Hooke and Huygens, each proposed a standard fixed point, one the melting point of ice, and the other the boiling point of water; but strangely enough, neither seemed to realize that *one* fixed point could not determine a scale. Suppose, with no scale for measuring distances, we *defined* a mile as the hundredth part of the distance from Tallahassee. The distance from Tallahassee *to what?* one would query. The difficulty is interesting to the student of thinking. Robert Hooke was sufficiently active in science to be well acquainted with Newton, Boyle, Halley and other leaders, and made some advances on his own account; and Christian Huygens was a genius who founded the wave theory of light, discovered the laws of the pendulum, invented the first accurate clock in the history of civilization, worked out the mathematically exact law of centrifugal force which we used earlier in dealing with planetary rotation and revolution, and laid the foundations of conservation of energy in the field of mechanical phenomena. Yet the necessity of defining *two* fixed points in thermometry eluded him! One can tell by this that it is never safe to speak of a discovery as simple or obvious *after the fact*. How can we, living in a world which is so largely the condensed imagination and genius of thou-

sands of great thinkers of the past, decide what should have been obvious?

A Frenchman, Dalancé, who used linseed oil as the expanding substance in his thermometers, made the necessary advance, proposing the melting points of ice and butter as the two standards with which to fix a scale. Anyone who has observed the gradual softening of butter of different grades in hot weather can judge how dependable its melting point would be as a fixed standard of temperature. Many curious standards — one the temperature of a cow — were suggested in the early days of thermometry.

It remained for a physicist of Danzig, Gabriel D. Fahrenheit, to produce (in 1714) the first accurate and precise thermometers. Using mercury in glass, he calibrated the scale into 180 equal divisions between the temperatures of freezing and boiling of water under standard conditions, and called the lower point 32 because, in his opinion, this would bring zero to the lowest temperature attainable in nature. Subsequent progress in low-temperature work may be judged by the fact that in recent years temperatures as low as 458 Fahrenheit degrees below zero have been produced. The familiar carbon dioxide snow of commerce, called dry ice because it evaporates directly from solid to gas without melting, maintains a temperature of approximately 112 degrees Fahrenheit below zero.

The location of the zero was no impediment, however, and Fahrenheit thermometers are in common use today in English-speaking countries. The boiling point of water under average atmospheric pressure at sea level is 212 degrees. Another scale, called the centigrade, is employed in scientific laboratories throughout the world and is the household scale in several countries. This scale, invented in 1742 by Anders Celsius, a Swedish astronomer,

FIGURE 26. Taking the temperature of a glass-melting furnace at a distance. The electric current flowing through a platinum wire in this optical pyrometer is varied until the glowing wire seems to merge with the molten glass which serves as a background. The instrument has been calibrated to read degrees of temperature. (Courtesy Pittsburgh Plate Glass Company.)

uses zero and 100 as the freezing and boiling points, respectively, of water, instead of 32 and 212.

Note, in passing, the internationalism of science. Italy, France, England, Germany, and Sweden contributed to the evolution of thermometry.

In more recent times, many other types of thermometers have been perfected. For standardization of ordinary instruments, scientists rely on a form of gas thermometer somewhat resembling Galileo's but without the serious disadvantages of his. The bimetallic thermometer is widely used. This consists of thin strips of two different metals, one on top of the other, welded together. When heated, the device bends into a curve, the metal that expands the more taking the outside of the curve where there is more room. Thus an index can be moved over a graduated scale, or an electric switch can be thrown automatically, as in heating or refrigerating devices, laundry irons, and intermittently flashing lamps. Electric thermometers, some so sensitive that they respond to the feeble heat radiation of the stars or of a man's head several hundred yards away, are in common use for taking temperatures at a distance and for measuring temperatures too high or too low for the mercury thermometer.

The Pressures of Gases

Fahrenheit had made the precise expression of temperature possible and thus prepared the way for the measurement of heat energy — a different quantity — as soon as the necessary additional ideas and facts should be obtained. Another aspect of nature, however, needed investigation: the nature of gases. Studies of gases have contributed greatly to our ideas of the nature of heat energy. Si-

multaneously with the evolution of thermometry, air was being studied seriously for the first time in history.

The Barometer. Evangelista Torricelli had the good fortune to be a pupil of Galileo for a short time before Galileo died. Later, noticing the fluctuations of a Galilean thermoscope under changing atmospheric pressure, Torricelli thought: Suppose there were no air at all, a vacuum, in the upper bulb? Then the atmospheric pressure would push the liquid up the stem until the column was so high that its pressure exactly equaled atmospheric pressure. Any change of pressure would cause the liquid to rise or fall. The effect which had been merely an annoyance and source of error in Galileo's device would now be the sole cause of action! Atmospheric pressure would be measured.

But how secure a perfect vacuum? Torricelli's answer was ingenious. Fill the whole tube with mercury to expel all air, and then never let any air get in! He accomplished this result by holding the opening of his long glass tube closed until he got it under the surface of mercury in the open dish. There is the barometer of today. The first barometer is, with merely minor improvements, the modern standard! Torricelli, in his grave these three centuries, might well be proud as the modern forecaster of weather reads his instrument every day and broadcasts the warnings of storms when the mercury column is falling.

Torricelli's discovery had important philosophical effects, quite apart from its practical value. The belief that nature abhors a vacuum was widespread. A vacuum had been held to be impossible; but, as the French scientist Blaise Pascal remarked on hearing of Torricelli's barometer, the existence of a vacuum above the mercury in the top of the tube proved that nature "does not shun a vacuum with so great a horror as many imagine." In producing

a vacuum, Torricelli helped to destroy a false animistic conception of nature akin to that which Galileo had combated when he proved the absurdity of Aristotle's idea that every object had its natural level in the universe and would go there like a homing pigeon if released.

At the same time, but independently of Torricelli, an interesting German, Otto von Guericke, burgomaster of Magdeburg, was inventing an air pump and demonstrating the magnitude of atmospheric pressure in spectacular exhibitions. In one famous display before Emperor Ferdinand III, von Guericke used two teams of eight horses each, pulling in opposite directions, to remove the hemispherical lid from an evacuated copper globe a little more than a foot in diameter. Eight horses against the atmospheric force on a few square feet! European scholars were excited by the new knowledge of the atmosphere and the possibilities of a vacuum. Pascal had the Torricellian experiment repeated on a mountain top and found, as he expected, a lowering of the barometric column. A new way to measure altitudes above sea level was being born. Accurate knowledge of the atmosphere that had bathed mankind and fed his lungs for hundreds of thousands of years was finally coming to light.

Laws of Boyle and Charles

Two exact laws of nature were now added to the meager complement which our brief summaries have pointed out. Robert Boyle of England, using Torricelli's technique of measuring air pressures with columns of mercury, discovered the law which is basic in the modern kinetic theory of gases. At constant temperature the volume of an enclosed mass of gas is inversely proportional to the pressure. In other words, double the pressure and the gas

is squeezed into half the space it formerly occupied. And so on. Mathematically, the law is most conveniently expressed by saying that the product of pressure times volume is a constant so long as the temperature remains unchanged. Boyle found this law by a long series of accurate measurements ending about 1662. Later, when the kinetic view of gases was proposed, supposing gases to consist of molecules moving at high speeds in all directions, the first test it had to meet was whether it agreed quantitatively with Boyle's law.

Many years later, but before the principle of conservation of energy had been finally established, a French physicist named Jacques Charles discovered how changes of temperature affect the pressure or volume of a gas. If the volume remains constant, the pressure increases by the same fraction for every degree the temperature rises. If the pressure remains constant, the volume increases by the same fraction for every degree the temperature rises. And if both pressure and volume are allowed to change, the product of pressure times volume increases by a certain constant fraction for every degree rise of temperature.

This latter statement is a combination of Boyle's and Charles' laws. The modern physicist states it as follows: The product of the pressure by the volume is directly proportional to the absolute temperature of the gas. All this needs amplification for full understanding. The importance of a knowledge of this law in designing applications in which the pressure of hot gas pushes a piston, as in steam engines and automobiles, will be obvious. For the moment, omitting practical and theoretical considerations of great importance, let us simply note that here was an exact and general law relating to temperature which any theory of the true nature of heat energy must rigorously satisfy.

Kinetic Energy and Work

Now we go back to still a third movement, one which paralleled the development of temperature measurements and the study of gases. Like a French chef, though with no pretensions to his Gallic artistry, we are assembling the materials for a meal. Kinetic energy and work are essentially mechanical concepts. Archimedes of ancient Sicily, who discovered two laws of mechanics, must have gained a notion of physical work from his studies of the lifting of masses with the lever, and he no doubt also had a concept of the efficacy for producing effects which a moving body possesses by virtue of its motion. These are matters of common observation. One does not need to know the laws of motion to recognize the advisability of dodging a truck. The difficulty faced later by Galileo and his immediate successors was to create and disentangle the concepts of force, momentum, kinetic energy and work, and define them exactly so that the laws could be found and expressed. The ideas were sorted out by the time that triumvirate of genius — Huygens, Newton, and Leibnitz, contemporaries all — had finished their labors, though arguments about terminology ran on for another century.

Momentum and Shock. Everybody knows that the shock produced by a moving body depends on the suddenness with which it is stopped. One has only to catch a ball to discover this. If the hand be skillfully withdrawn in a yielding manner, a swiftly thrown ball can be caught without great shock; but if the inept hand uncompromisingly holds fast, or even slaps at the ball, so as to bring it to rest in the shortest possible time, a great force may be exerted on the hand. By analyzing such problems, Isaac Newton concluded that a moving body possesses an efficacy of some sort that is equal to the product of its mass by its velocity. We call that

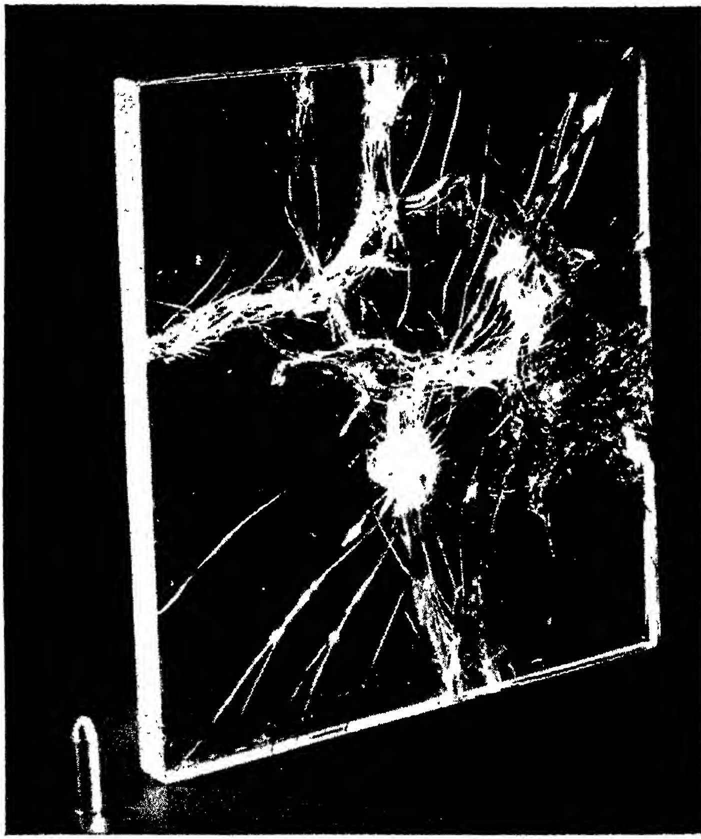


FIGURE 27. Shock is proportional to the rate of change of momentum. This laminated bullet-proof glass was shot once with a 45 calibre revolver. No glass left the reverse surface. Note that the transparent adhesive between the glass layers does *not* act as a cushion to reduce the rate of change of momentum. It prevents any fragments from flying. (Courtesy Pittsburgh Plate Glass Company.)

quantity *momentum*. Doubling the velocity doubles the momentum. Also, a great mass moving at slow speed possesses the same amount of momentum as half that mass moving twice as fast.

The *force* which a moving body exerts is proportional to the rate at which its momentum is being reduced. Compare landing in a fireman's net when jumping from a second-story window — and landing on a concrete sidewalk. The yielding net destroys the body's momentum at a slower rate than the concrete does. Similarly, when the foot comes down on a tile floor, the momentum is destroyed so suddenly that the force on the foot is greater than that which a more yielding floor, such as wood, would exert; hence running or dancing on tile, even if the surface is smooth, is rather hard on the feet.

Kinetic Energy. Now suppose we toss a ball vertically upwards with a certain starting velocity, then repeat the experiment with twice the velocity. We find that doubling the starting velocity doubles the time of ascent but quadruples the distance of ascent. In other words, the ball now continues to rise for *twice* as long a time but rises *four* times as far. Since the force of gravity, which is what causes the momentum to be reduced to zero by the time the ball reaches the top of its flight, remains unchanged, the rate of loss of momentum must be the same in both cases. Hence the ball which was tossed upwards with the doubled velocity must have possessed twice the momentum, since, at the same rate of loss, it took twice as long to lose that momentum. But the ball must have possessed *something besides momentum* at the start — something proportional, not to the velocity, as momentum is, but to the square of the velocity; for with double the velocity it was able to lift itself four times as far against gravity. Doubling the velocity quadrupled the efficacy for doing work against gravity. In short, the body possessed *kinetic energy,* and the kinetic energy of a mov-

ing body, which is its capacity for doing work, is proportional to the square of its velocity.

If a leisurely re-reading of the preceding paragraphs should prove necessary, the reader may console himself with the knowledge that the underlying issue occasioned a half-century of debate between the followers of two intellectual giants of the seventeenth century, René Descartes and Gottfried Wilhelm von Leibnitz. Indeed, the argument was not settled until the appearance of a penetrating analysis of motion written by a Frenchman who, only twenty-six years earlier, had been picked up as a foundling on the doorstep of the church of St. Jean le Rond in Paris. Jean le Rond d'Alembert disposed of the question in 1743, in the preface of his classic treatise, by pointing out that the difficulty was partly a matter of definition of terms.

Definitions Versus Reality

True, we implied a definition of work. *If* work be defined as the force multiplied by the distance (the accepted definition), then when the moving body lifts itself four times as far it does four times as much work. *If* energy be defined as the capacity for doing work, then to do four times as much work requires four times as much energy. But experiment shows that to do four times as much work with an engine of an unvarying efficiency requires four times as much fuel. Now, work may be a definition, but fuel is not. Fuel is real. We might conceivably say that work is half the force multiplied by the distance, or a million times the force times the distance. All the numbers used in work and energy would then be changed; but the *relations* would not be changed, and neither would that fact about fuel. But if we tampered with the relation used in defining work, say by calling it the

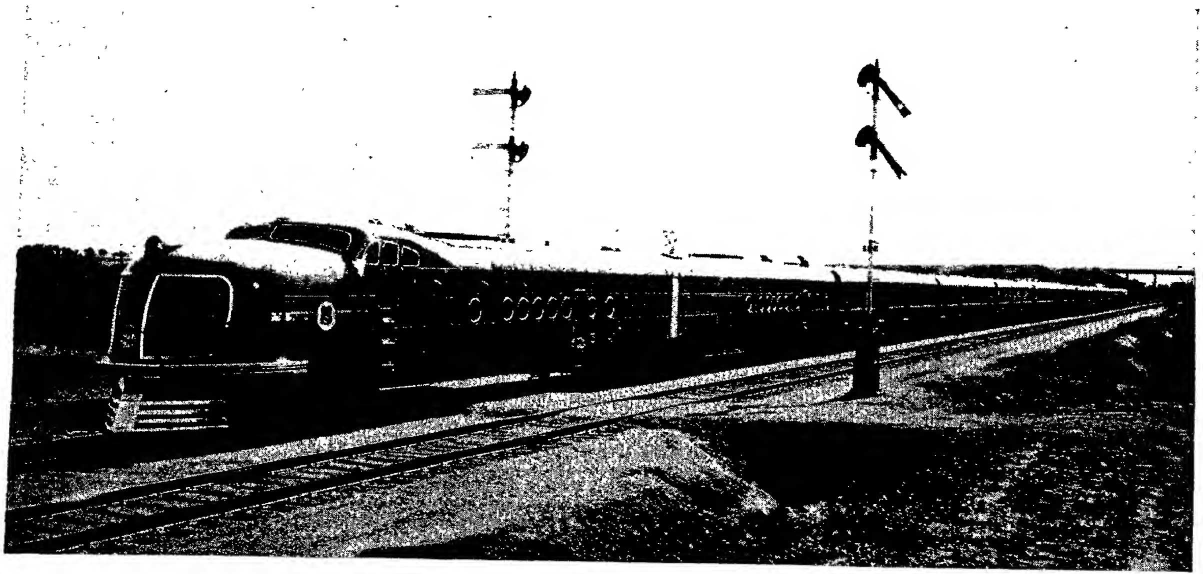


FIGURE 28. Reducing kinetic energy. This Union Pacific train is made largely of light aluminum alloys. Lightening a train or automobile reduces its kinetic energy at a given speed and makes both starting and stopping easier. Any vehicle moving at 60 miles per hour possesses enough kinetic energy to lift itself to the top of a building about twelve stories high. (Courtesy Aluminum Company of America.)

force times the cube root of the distance, our calculated results would not agree with nature.

We reach the same conclusion by reverting to our illustration of the ball that was tossed upwards into the air. The brute fact is, that doubling the starting velocity of the ball quadruples the height to which it lifts itself; tripling the velocity causes the rise to be nine times as great; and so on. Therefore the kinetic energy, at whose expense the work against gravity is accomplished, must be four times as great when the velocity is doubled; nine times as great when the velocity is tripled; etc. This means that kinetic energy is proportional to the square of the velocity. That *square* is evidently a fact of nature.

Experiments with objects of different masses show that the kinetic energy is also proportional to the mass of the moving body. Taking all the facts into account, we find that kinetic energy equals one-half the product of the mass by the square of the velocity. (Of course we must use a consistent set of units to avoid discrepancies.) To cite one illustration, if we omitted the *square* in the statement we should conclude that a runner racing twenty laps, say, around a small indoor track would waste so much energy changing from *plus* to *minus* velocity every time he rounded the curve at each end of the gymnasium that he would burn up many times as much food or body substance as in running the same distance straightaway, and take many-fold as much time, which is simply not true. But the *square* of a real number is *plus* whether the number itself is minus or plus, hence the runner does not lose his kinetic energy when changing his direction from north to south, say, on rounding the curve. This agrees with experience.

We have devoted so much space to work and kinetic energy because these are fundamental in the discussions of all the forms of energy with which we shall be dealing. The concepts of work and

Figure 29. The performance of *work*. This huge transformer, built to deliver 287,000 volts at its high-voltage side, is being moved at Boulder Dam. Work of lifting equals the weight multiplied by the vertical distance. (Courtesy of General Electric Company.)

energy arose in the manner described. Discussions spread over a century are summarized in this small section. Thus it can hardly be called complete. But we have seen that man did not define work and energy arbitrarily. Rather, *he found out what they are!* A captious critic might suggest that we change our definitions of *both* work and energy simultaneously. True: but then we should be talking about something else. We want to deal with reality, with the real world of nature.

Note, in conclusion, that bodily fatigue or feeling of weariness did not enter into our argument. If you forget to set your suitcase down on the floor when waiting for a train your arm may grow tired, but you are doing no work until you lift it. When you lift it, the work you do is the weight times the vertical height. Lifting a fifty-pound suitcase 2 feet requires the performance of 50 x 2, or 100 foot-pounds of work. If you lift it twice as high, you do twice as much work. Whether the increase of your weariness becomes twice as great, the psychologist cannot yet say. But you use up twice as many foot-pounds of energy in the act, and thus help to break down any resistance that you may have to thoughts of the next meal. In short, the concepts of work and energy are objective, not subjective — and they are exact. Let us use them consistently and see where they take us.

Heat Quantity

One of the reasons why physical science succeeds in dealing with intangibles is that it has developed the technique of defining them objectively, measuring them accurately, and applying them practically, without waiting for a full knowledge of their essential nature. The expression of heat quantity is a case in point. Man was measuring it and accurately predicting results long before he knew what heat was.

Suppose we pour equal masses of water and mercury, say a pound of each, into a vessel which is so poor a conductor of heat, and so well insulated, that any escape of heat from the liquid contents may be neglected. Let the water, just before being shaken up with the mercury, have a temperature of 100 degrees centigrade, the mercury zero degrees C. The two liquids speedily come to the same temperature. Since there is one pound of each, one might possibly expect, at first thought, that the final temperature would be halfway between those of the hot water and the cold mercury, which would be 50 degrees C. But the temperature is actually 96.8 degrees C. The pound of ice-cold mercury has cooled the pound of boiling water only 3.2 degrees, while the pound of hot water has warmed the pound of mercury 96.8 degrees. Evidently water has a much greater *capacity for heat* than the mercury has.

We reach the same conclusion by another simple experiment. Suppose, using insulated vessels like that just described, we warm a pound of water with a small electric immersion heater, then repeat the test with a pound of mercury. If the conditions of heating are the same in the two tests, we discover that it takes thirty times as long to warm the water a few degrees as to make the mercury the same number of degrees hotter.

Latent Heats of Melting and Evaporation

If we used other pairs of materials instead of water and mercury, we should find similar differences. The numbers obtained would vary, but the basic fact that different substances have different capacities for absorbing, containing and giving up heat would appear every time. And if we embed our electric heater in a pound of ice at zero degrees centigrade, in the same insulating vessel, we find that we can let the heater operate as long as would be required to

raise the temperature of a pound of water 80 degrees, before any rise of temperature occurs at all! The ice absorbs great quantities of heat merely in melting, which means changing from a solid *at zero degrees* to a liquid *at zero degrees*. That is the reason why ice is so much more effective as a cooling agent than an equal weight of ice-cold metal. If the room temperature is 21.1 degrees C. (70 degrees F.) a given mass of ice originally at zero degrees can absorb 40 *times* as much heat before losing its cooling ability as can an equal mass of cast iron that is as cold as the ice at the start.

The opposite effect occurs when a liquid freezes. Then it gives up heat, so that freezing is, in a sense, a warming process. In electric refrigerators which have accessible radiators, one can feel with the hand the effect of the heat that is removed from whatever you have placed in the freezing compartment.

Similar phenomena occur when a liquid evaporates into a gas, or when vapor condenses into a liquid, as in the formation of dew. Merely to evaporate a pound of water at 100 degrees C., *without making it any hotter,* requires as much heat as would raise the temperature of 540 pounds of water — more than a quarter of a ton — one degree C. Incidentally, we see the futility of turning up the gas to keep the water boiling violently when cooking. If the water is boiling gently it is just as hot as when boiling vigorously, and the potatoes cook just as rapidly. Additional heat forced into the water merely serves to evaporate water faster without raising the temperature.

And if we force a liquid to evaporate rapidly without a special source of heat, perhaps by means of a stream of air, as when holding a wet finger in the breeze, or by reducing the pressure as in electric refrigerators, the heat of evaporation is absorbed from the remaining liquid and from the surroundings, which are therefore cooled. The evaporation of dry ice keeps it cold until it disappears. Con-

versely, when vapor condenses to liquid it gives up heat. Thus live steam condensing on the hand, though no hotter than the boiling water it came from, gives a much more severe burn for an equal exposure.

What Is a Calorie?

We see why early experimenters, beginning with the enthusiastic group of Galileo's former students who founded the Florentine Academy, arrived at the notion that heat and hotness are not the same thing. The facts and ideas given above accumulated very gradually. When, several decades before the American Revolution, Joseph Black, one of the great founders of chemistry, announced in Scotland that mixing a pound of ice at zero degrees C. with a pound of water at 79.7 degrees gives two pounds of liquid water *at zero degrees,* which is true, the news was received with astonishment. Ideas of heat had to be revised. We have changed Black's results from Fahrenheit to centigrade, and corrected the experimental error which he made.

How then was heat to be defined? Men did not yet know what it was. It could not be defined as that which makes things hotter; for, as we have seen, the addition of heat does not always cause a rise of temperature. Yet obviously there existed in nature a thermal quantity different from temperature, an agency to which temperature changes *sometimes* gave a clue.

The solution is complicated; but a practical unit of heat could readily be defined. A calorie is the amount of heat that must be added to 1 gram of water to raise its temperature 1 degree centigrade, or the amount that must be removed from 1 gram of water to lower its temperature 1 degree C. With the aid of this definition, we can deal also with those heat operations in which the addi-

tion of heat does not produce a rise of temperature. For example, by melting ice in a bath of warm water we can tell by the cooling of the water how much heat disappeared in causing the melting.

Do not confuse the calorie defined above, with the unit which is used on menu cards and by writers on dietetics. The energy values of foods are usually expressed in kilogram-calories. One kilogram-calorie is the amount of heat required to raise the temperature of 1000 grams (2.2 lbs.) of water 1 degree C. This larger unit, which equals 1000 calories, is often written merely *calorie.*

Peculiarities of Water

It is interesting to note that we use water as a standard substance in defining the unit of heat, though water is a remarkable exception, far from average in its capacity for absorbing heat. It has a greater heat capacity than any metal except hot lithium, and greater than any liquid except ammonia. For example, at ordinary room temperature mercury has a thermal capacity, or *specific heat,* of 0.0331, cast iron 0.119, methyl (wood) alcohol 0.57 calorie per gram per degree centigrade rise of temperature. The value for water is, by definition, exactly 1.0000 at 15 degrees C.

Thus almost all the materials in nature are easier to warm, and easier to cool, than water is, so far as the quantities of heat involved in a given change of temperature are concerned. Adding alcohol to the water in an automobile radiator to prevent freezing in winter has a minor disadvantage: the solution has a smaller heat capacity than pure water and therefore is more quickly heated by the engine. The great thermal capacity of water exerts a profound effect on climate, tending to moderate the conditions by retarding both sudden drops and sudden rises of temperature.

Water is exceptional in another respect, entirely apart from its

great thermal capacity. On cooling from the higher temperatures it contracts, as most substances do — but after it reaches four degrees centigrade any further cooling causes it to expand! It also expands when freezing, instead of contracting as most substances do. Thus ice floats in water, and lakes and rivers do not freeze solidly from the bottom. Otherwise large areas of the present temperate zones would probably become uninhabitable by men, not to mention the fish.

Antoine Laurent Lavoisier

Let us now choose a point of vantage in history from which to observe the marshaling of forces that were to lay bare the nature of heat and thereby establish the principle of conservation of energy. May 8, 1794, is a memorable date. On that day, one hundred and seven years after the appearance of Newton's *Principia,* Antoine Laurent Lavoisier, who shares with John Dalton the honor of being the Isaac Newton of chemistry, died on the Paris guillotine at the hands of the Revolutionary Tribunal. In those days of terror, France thought she did not need her greatest chemist.

Lavoisier had changed chemistry into an exact, quantitative science. He had named hydrogen and oxygen and recognized them for what they are, true elements of nature. By skillful use of the balance he had proved that matter, through all its chemical transformations, even burning, remains constant in quantity, losing nothing material and gaining nothing. Thus he had established *conservation of mass,* a sweeping principle on which clear thinking in the whole of chemistry was to rest until certain recent discoveries in the field of radiation rendered a slight — very slight — modification necessary. As a consequence, he had destroyed the doctrine of phlogiston which had beclouded chemical views for a century.

Caloric Survives Phlogiston

Curiously enough, while dethroning one non-existent entity, Lavoisier lent his authority to another by conferring the famous name *caloric* on a fictitious heat-substance which, like phlogiston, had a long history of trouble-making. Similarly, a century earlier, Newton had delayed the acceptance and development of Huygens' wave theory of light by insisting that light consisted of streams of material particles.

Phlogiston was the fire-element of the chemists. It was a substance that escaped when materials burned. Far from being weightless, it had *negative* weight. Like Aristotle's fire, it was intrinsically light, not heavy. When it entered a body it made that body lighter; when it departed it left the body heavier. To the chemists of the eighteenth century, this seemed the only way to interpret the fact that when a metal was burned, or roasted in air, the solid material increased in weight. The *loss* of matter having a *negative* weight made the residue heavier. The union of oxygen with metals to form oxides, such as iron rust, and thus increase the weight of solid matter, was not understood. Priestley prepared the gas oxygen, and Cavendish made water by exploding a mixture of the two gases, hydrogen and oxygen, in a glass flask; but the oxygen was called dephlogisticated air, and the hydrogen inflammable air.

An interesting paper might be written on the role that imponderable substances have played in scientific thought. Many physicists now actively engaged in their profession spent long hours as students mastering the intricacies of an all-pervading ether that possessed the remarkable combination of properties of being solid, elastic, rigid, weightless, transparent, and incapable of offering the slightest resistance to the motions of the planets. That ether has

followed phlogiston and caloric into the discard, and one may find it interesting to speculate on possible revisions that the curved space of relativity may undergo in future centuries. Finality is a dangerous word. Despite the confidence engendered by the achievements of physical science in recent generations, to look back condescendingly on the phlogiston and caloric schools of Lavoisier's time would be to do a grave injustice to the memory of able thinkers.

Caloric was the heat-substance that flowed from body to body, leaving the one colder, raising the temperature of the one it entered. Since heating an object does not make it heavier, caloric had no weight, either positive or negative. Here there was a marked difference between phlogiston and caloric. The difficulty of accounting for the disappearance of heat when melting or evaporation occurred was cleverly surmounted by assuming that the caloric, supposedly a true substance even if weightless, entered into chemical combination with the melting or evaporating material. Thus the phenomena of latent heat, as well as the fact that when ordinary transfer of heat occurs the gain of heat by one body equals the other's loss, were both accounted for by caloric.

Boring Cannon and Rubbing Ice

So far, so good. Caloric satisfied many facts. But Benjamin Thompson, an expatriated American who left the country at the time of our Revolution and rose to fame in Europe as Count Rumford of Bavaria, London and Paris, bored some cannon in Munich while serving as Bavaria's minister of war. Not only did he bore cannon. Surprised at the large amounts of heat produced by the drilling, Count Rumford purposely dulled the drill, surrounded the brass with a water jacket, and then, to the astonishment of

spectators, proceeded to bring approximately 19 pounds of water to the boiling point in two and a half hours of drilling. The fire-drill of the savages of antiquity was coming into its own!

Surely, Rumford reasoned, a *substance* could not be created by the mere act of turning the drill. The moving drill must communicate motion to the invisible particles of which the brass is composed, and that motion is heat.

The calorists had a ready answer. The block of brass, they said, contained at the start a certain amount of caloric. The blunt drill changed some of this brass into powder and thus lowered its heat capacity. The amount of caloric already in it was now too great to permit it to remain at the same temperature, so it became hotter. No heat had been created.

The ingenuity of this answer will be appreciated if one will recall our illustrations of heating water and mercury. We found that the amount of heat required to warm some water a few degrees would make an equal mass of mercury much hotter. Suppose that by waving a magic philosopher's stone we could suddenly change the water into mercury. With its new smaller heat capacity, the material would now be forced to become hotter merely by virtue of the heat already in it.

Accurate measurements of the specific heat of brass in both the block and the powder form could of course decide the fate of the calorists' explanation; but Sir Humphry Davy of England chose a different method of demolishing the argument. He rubbed two pieces of ice together. A simple experiment — but the ice melted to water! Water was known to possess more heat, pound for pound, than ice. Black's work on the latent heat of melting had proved that. The extra heat could not have leaked in from the surroundings; for Davy had purposely kept everything except the ice below the freezing point, and heat does not flow from colder

to warmer bodies. The heat had been *created*. The newly born heat had been created by friction, which is to say, by work. Rumford's ideas received unanswerable vindication. If work could create heat, heat must be energy, not a substance.

The Mechanical Equivalent of Heat

Sir Humphry Davy obtained his striking result in 1798, when he was twenty years old; but so firmly entrenched was caloric that it was a long time dying. For a number of years only Rumford, Davy and Thomas Young seemed to grasp the full significance of the creation of heat by work. Indeed, it was not until 1843, when James Prescott Joule, an English brewer and brilliant experimentalist who missed an important university professorship in Scotland because of a slight personal deformity, announced the *quantitative* relation between heat and mechanical energy, that the true nature of heat began to be recognized generally.

Joule performed a great number of ingenious experiments in a lifetime of research; but the one that served best to immortalize his memory was, like that of Davy, a marvel of simplicity. He stirred water with a paddle-wheel! The water grew warm from friction; the heat was painstakingly confined and measured; the paddle-wheel was driven by slowly falling weights so that the work expended in friction could be accurately measured in foot-pounds. The amount of heat proved to be precisely proportional to the amount of work done to generate it. Joule was now able to inform the world with incontrovertible evidence that heat was a form of energy. He could state precisely *how many* foot-pounds of mechanical energy a calorie of heat energy equaled, or what fraction of a calorie a foot-pound of work would produce.

Count Rumford died too soon. In 1804 he wrote that he expected

to see caloric " interred with phlogiston in the same tomb." But ten years later he died, and Joule did the honors at caloric's grave. In doing away with the imponderable substance Joule earned an imponderable monument for himself — the recognition which science has gratefully accorded him by substituting a small letter for the initial of his name. The *joule* of energy is an absolute unit in common use. One calorie of heat equals 4.185 joules, or 3.087 foot-pounds of energy. This is the mechanical equivalent of heat.

Conservation of Energy

The principle of conservation has stolen up on us. Under the innocent-sounding subtitle, The Mechanical Equivalent of Heat, the secret has been revealed. For with heat all forms of work can be done, and conversely, other forms of energy can be converted into heat. Calories and foot-pounds are therefore fundamental, and one is equal to exactly so many of the other. When you climb the stairs, precisely one calorie disappears from your body, in addition to all other losses, for every 3.087 foot-pounds of work that you do. When a heat engine does work, say in hoisting a load fastened to a rope running over a pulley, heat disappears from existence in that same proportion, over and above all the waste due to lack of perfect efficiency. The energy is stored in the lifted mass as *potential* energy; we can get it back as heat by letting the mass fall to produce impact and friction. It is possible to calculate the maximum amount of work that can be done with a certain amount of heat, or how much heat will be produced in bringing a moving body, say an automobile, to rest by applying the brakes. The mechanical equivalent of heat has been measured by every means that the ingenuity of man could devise: by compressing air; by

letting the compressed air expand, do work, and cool itself; by electric and magnetic methods; by friction in innumerable arrangements; by hammering metals to make them hot — and always the same result is obtained, showing that energy is neither destroyed nor created, but merely changed from one form to another.

Illustrations of Conservation

When you use a lever to multiply the effect of an applied force, the resistance overcome may be many times as great as the force that you apply on the long arm of the lever, but the distance through which you push your end is precisely that same number of times greater than the distance through which the load rises; hence the work accomplished, which equals force times distance, is no greater than the work done. We can deduce the law of the lever directly from the law of conservation of energy, without knowing anything about moments of force. Often one does not need to study the details of a proposed action or machine to determine whether it would work. Merely apply the law of conservation to the initial and final conditions, overlooking the intervening actions. With no knowledge of electric generators, one knows beforehand that the armature will be harder to turn when it is generating electricity than when idling. If a hand-driven generator is available, let an assistant close a lamp-switch to draw energy from the generator after you have brought the coil to running speed. The bearings are as well lubricated now as before, but the hand on the crank feels as if brakes had been applied. The coil is now delivering energy, there must be compensating work. One almost seems to feel the great principle of conservation with his muscles.

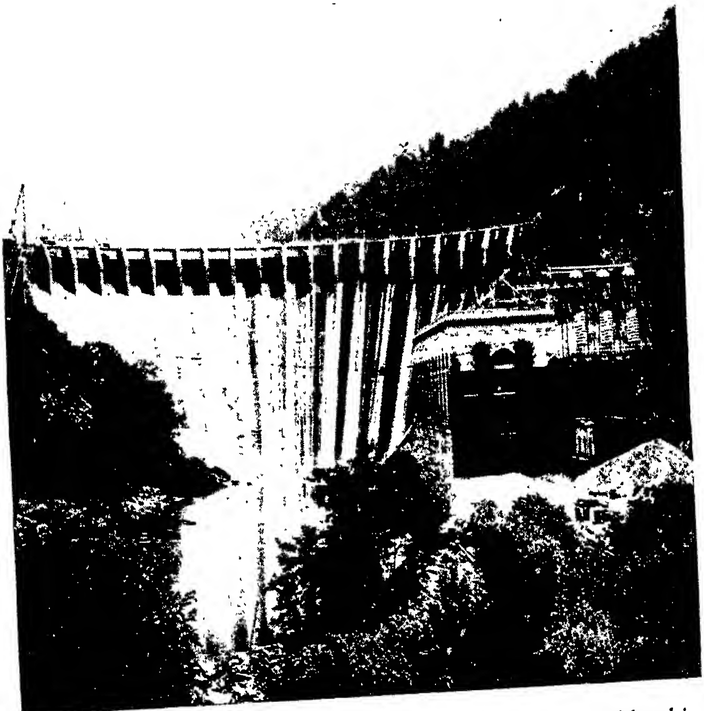


FIGURE 30. Conservation of energy. The energy supplied by this hydro-electric station on the Little Tennessee River System is not created, but transformed. Sunlight supplied the energy that vaporized the water and carried it to the heights. (Courtesy Aluminum Company of America.)

When the radiant energy of the sun warms some water, lifts it up into clouds from which it eventually falls to flow over the dam, conservation of energy applies. When some of the kinetic energy of that moving water is converted into the kinetic energy of the rotating armature of a generator, thence into the energy of moving electrons and finally into the heat and luminous energy of a lamp in your home, conservation continues to apply to every step in the intricate series of transformations. The chimera of perpetual motion of the sort that inventors talk about has vanished from the thinking of all informed men, though asylums continue to receive their quota of persons who have tortured themselves into insanity with vain attempts to circumvent the great principle that Joule established.

When you pay your electric bill at the end of the month you pay in terms of energy. One kilowatt-hour of electric energy equals 2,655,200 foot-pounds. You can calculate from this how much a foot-pound of work is worth in your community at the prevailing rate, hence how much you owe yourself when you lift your body up a certain flight of stairs. Or you can express the result in terms of food, if you like. The daily ration recommended for a man engaged in moderate muscular work is 3,300,000 calories. This is the energy value of about three pounds of beefsteak, or, by Joule's equivalent, of ten million foot-pounds of work, or 3.8 kilowatt-hours. A 150-watt lamp operating 24 hours consumes about that much energy. What is your wattage?

Conservation and the Nature of Man

The discovery of the principle of conservation of energy inevitably exerted a profound influence far beyond the confines of physical science. The concept of a universe rigorously obeying a

single physical principle in every action and corner of its great expanse — in every blood corpuscle and every star — did more than any discovery since Newton's gravitation to persuade mankind that the material world in its entirety was held in the firm grip of inviolable law. Our innocent-sounding question of the preceding paragraph — What is your wattage? — was now raised in all earnestness. In many minds the implications of the answer given by conservation were carried to extremes of materialism which not only alarmed spiritual leaders but greatly exceeded the limits of experimental proof. The successes of physical science, the impressive scope of its laws, the exactness of its methods, the rigorous tests to which it subjects an idea before accepting it as true — all these have operated to give physics a tremendous influence in shaping thought. Therein one finds at once a tribute, a danger, and a responsibility.

Throughout the century ending with the discovery of conservation of energy the predominant view of the relation of matter to life was that the materials composing the human body are, by virtue of life and mind, endowed with the power to transcend the laws of physics and chemistry, to hold them in abeyance or even violate them. This view, called *vitalism,* received its death blow at the hands of the discoverers of conservation of energy. The inference was immediately drawn that man is a sort of heat engine, and exhaustive measurements to test the idea were soon being made. Experiments of many kinds were tried. Rabbits were chased around yards, and subjected to measurements before and after exerting themselves. Guinea pigs, rabbits, dogs, men were shut up — separately — in insulated cages of various designs, with or without ice in the cage to absorb the bodily heat. The energy values of foods eaten were determined; amounts of work done were measured; heat losses from the skin and lungs by radiation,

convection, conduction and evaporation were evaluated. The carbon dioxide exhaled was weighed. The number of calories of heat yielded by the oxidation of enough food-product to form that carbon dioxide was accurately determined. Rubner, Wood, Atwater, Rosa, Benedict are the names of a few of the experimenters in this field. The later results agreed with conservation of energy to within a fraction of one percent—a remarkable agreement considering the difficulty of heat measurements—and this agreement left no allowance of energy for mental activity. The conclusion could not be avoided that man, in a purely physical sense, is indeed to be explained in terms of the laws that apply to inanimate matter. The false theory of vitalism was exploded. Also, unfortunately, a wholly materialistic view of man as a machine began to be held in certain quarters—a view resembling the picture of man painted in the eighteenth century by de la Mettrie, author of *l'Homme Machine* (1748) and his immediate predecessors and followers; only now the materialistic view claimed the authority of scientific proof and so was vastly more influential.

At this point the reader, if interested, might well refer again to those portions of our introductory chapter in which the limitations which physical science sets for itself were discussed. It seems perfectly certain that the matter composing animate bodies, including man, obeys the laws that inanimate matter obeys; but this fact does not preclude the existence of something that science has not yet gotten its fingers on—something which causes, and accounts for, that great difference between man and his environment which seems to be one of the most striking facts of observation known today. To dismiss *mind* as non-existent because we cannot weigh it, and at the same time to leave the music of a Beethoven and the poetry of a Browning unexplained, seems unscientific. Even phlogiston and caloric were not relegated to limbo until rigorous

experimental evidence of a *positive* nature — evidence requiring no correlation coefficients as substitutes for exact laws — had proved their unreality.

Beyond exposing the more obvious frauds and shams, physics, as an experimental science, can give no authoritative answer to questions of spiritual reality. It can, however, and seemingly should, point out that within its own field it has not averted its eyes from unseen imponderables. Setting two facts of observation side by side, the light of a lamp filament on the one hand, the existence of physical science itself on the other, can one say that the one shows the reality of energy more surely than the other testifies to the reality of something capable of conceptual thought and flights of genius? The laws of physical science, wide though their scope, rigorous their application, should be used critically, with a just regard for the limitations inherent in the methods that bring them to light.

A Triumph of Youth

The fertility of the principle of conservation of energy will become increasingly clear as we go on to deal with the structure of matter and with applications of energy in the modern world. In this chapter we have been trying to lay a background and follow the progress of ideas that culminated in the law of conservation. A restricted sort of conservation was clearly in Huygens' mind when he published the laws of pendulums in 1673, and as early as 1775 the French Academy of Sciences resolved to receive no more *mechanical* schemes for perpetual motion. Before that, Francis Bacon, Newton, Boyle, Hooke and Descartes had all looked on heat as a mode of motion.

But caloric intervened, and thinkers generally offered resistance

to the truth. Even Joule, coming before the Royal Society of London with numerical proof in his hands and the principle burning in his head, was saved from temporary oblivion only by the insistence of Lord Kelvin, then a very young man, that his ideas be considered. Von Helmholtz of Germany reached the principle on the heels of Joule but was refused publication at his first attempt. Robert Mayer of Germany, who, unknown to Joule, began a year ahead of the Englishman to seek a hearing for the same great law, finally attempted suicide in despair and spent two years of suffering, cruelly treated, in an asylum for the insane. The world found it hard to adjust its thinking to so fundamental a principle in all its beautiful generality. The oldest of the three discoverers was twenty-eight when he first sought hearers on the subject, the youngest twenty-five. It was youth against age, and in this case the truth was with the young.

Chapter 7

ATOMS AND MOLECULES: CHEMICAL TRANSFORMATIONS

Now that we have added the principle of conservation of energy to the complement of tools which we can use in prying into the universe to find out what it really is, where do we stand in regard to the problem of reality that was raised with a flurry of trumpets at the beginning of the fifth chapter? We have reached clear ideas of work and energy. We have accepted — because the evidence left no escape — the fact that heat is energy. We know now that, in terms of energy, one never gets something for nothing. The names of other forms of energy have been mentioned — electric, magnetic, radiant, chemical — but no evidence has been adduced to reveal their nature. Even heat itself, to which nearly a whole chapter was devoted — What is heat really, other than a rather mysterious agency that can do work? We have said hardly a word about the nature of matter. Matter has been taken for granted. Is matter something that has energy? Or is energy something that has matter?

Here we enter the fascinating field of modern physical science. Molecules, atoms, electrons, protons, neutrons, positrons! These words, even the last two, seem to be already the common property of newspaper readers. If our purpose were merely to intrigue the reader, we could plunge at once into a bewildering panorama of wonders beside which the fondest dream of the medieval alchemist brewing his philosopher's stone would seem stodgy, indeed. Who is not familiar with the externals of modern physics and chemistry? Heavy water; artificial radioactivity; television; five-million-volt

lightning in a laboratory; robots to steer airplanes in blind transcontinental flight; rays that cure, rays that kill, rays that show the bones as if the flesh were glass; inaudible sounds that sterilize water and kill fish? Rayon, pyralin, duralumin, bakelite, cellophane, lucite, rustless steel, high explosives that can be hammered with safety — all the marvelous new substances that issue in a seemingly endless stream from the chemist's workshop, never before seen by man? Who has not read of the centuries it would take the population of Chicago to count the electrons that flow in one second through the filament that one reads by, or of the photoelectric cells to which it is all one whether they make pictures talk, enable the blind to read ordinary print, open a world's fair with forty-year-old starlight, or politely swing the door ahead of the waitress to protect her tray? Who has not twirled the dial until some local electrons began to oscillate precisely in step with other electrons that were fluctuating rhythmically in a vacuum tube across the state or around the sphere?

Names Versus Reality

We shall not deny ourselves the pleasure of considering the striking successes that have attended man's ceaseless struggle to make his physical environment do what he wills; but we are at least equally interested in ideas. What right have we to speak of atoms and electrons? It is so easy to accept a name in lieu of understanding. How often do we give a mystery a name and then use the name until we end by thinking the name explains the mystery? Phlogiston, caloric, the ether, atoms, electrons, curved space, inferiority complex! Are they all in the same boat, mere names, confessions of ignorance? Or are those that have not gone out of use the symbols of something that is real? If so, what is that reality,

and how do we know? Ideas are not necessarily as difficult as the apparatus used in testing them. Rumford bored brass cannon, Davy rubbed two pieces of ice together, Joule stirred some water — and heat was proved to be energy. Are there equally simple experiments that show what matter is?

Sitting in an armchair, reading this, sipping coffee between paragraphs, one might be pardoned for thinking that we are manufacturing difficulties. How substantial everything seems! You grip the padded arm of the chair. Why all this talk about matter? you ask yourself. *There* is matter: you can squeeze it with your fingers. Anyone knows what the chair is made of: mohair, wood, springs. And now this book is going to say that I'm sitting on electricity and empty space, I can feel it coming. A breeze comes through the window. Of course I can't see the air, but it pushes the pages. That's not mysterious. Setting down the coffee cup on the end-table you notice an old ring in the varnish, reminder of a careless moment. You rub the edge of the ring with your finger. Nothing: just a little varnish dissolved off. The aroma of fresh coffee boiling in the kitchen reaches your nostrils. Nothing: just a smell. Quite a lot of smell, come to think of it. It probably fills the whole house, and almost all the coffee still back there in the pot. I suppose I'll hear that the smell is electricity, too. The reading lamp dims suddenly, growing yellow, then becomes very bright and white. I wish they'd keep the power steady. Just carelessness, probably: it ought to be easy to keep the power steady. The cat jumps into your lap and plays. Look out, there, cat! You're getting too strong to play like that. I'll get some antiseptic in a minute. You squeeze your finger to cleanse the scratch from within. Queer material, this living flesh: it hurts, and it grows. You twist the flesh a little this way and that, around the hard bone. Quite substantial. The fingernail seems queer, too: it grows, but it

doesn't hurt when you cut it. I wonder if it keeps itself warm? When is matter really dead, I wonder? I wonder. . . .

A commonplace soliloquy — but only through centuries of thought have some of the questions that lie within it, expressed or implied, found answers; and only rashness would venture to predict how many centuries will be spent in answering the remaining. Let us see what is known about the structure of matter.

Boyle Defines an Element

We come now to an idea that lies at the heart of modern science. One is tempted to say, civilization. To know whether matter at bottom is continuous, like space and time, or composed of small ready-made interchangeable parts, is more than a philosophical concern. Without a true picture of the structure science could not foresee the possibility of the new chemical substances that lie implicit but unrealized in the fertile storehouse of nature. Leucippus, Democritus and Lucretius of antiquity suggested, without adequate evidence, that matter is atomic at bottom. Isaac Newton developed the idea in his *Principia* in a thoroughly scientific though unsuccessful attempt to explain the pressure of gases as the effect of atoms which repelled one another according to a certain law. It remained for that great triumvirate of chemists, Dalton, Berzelius and Avogadro, to establish the atomic theory on a sound basis of quantitative proof. The debt that civilization owes these chemists can be partly realized when one recalls that only in the century since they did their work has chemistry made those spectacular advances which we of today accept as if they were automatic.

Robert Boyle, Irish-born contemporary of Newton, had given the modern idea of a chemical element in his *The Sceptical Chymist,* published in 1661. Concluding a now-famous passage

on the subject, Boyle said: "I must not look on any body as a true . . . element which is . . . resolvable into any number of distinct substances." Thus the white granular material which we use as table-salt, despite its deceptively innocent appearance, cannot be considered an element; for by suitable means it can be decomposed into two elements: one the unpleasant acid-forming gas chlorine, useful in disinfecting and bleaching, the other the soft silvery metal sodium, which is so violent in action that it is stored under oil in hermetically sealed cans to prevent contact with the atmosphere. The sodium and the chlorine are *elements,* since they cannot be decomposed into other substances; and the table-salt is a *compound* of the two, called sodium chloride.

Chemical Change Versus Physical Change

The salt which we used to illustrate Boyle's distinction between elements and compounds furnishes striking evidence of the amazing possibilities of chemical change. Sodium is so active a metal that one would not dare to grasp it with his bare fingers — at least not a second time. And as for chlorine: On April 22, 1915, the Germans began using, as their first poison gas, great quantities of chlorine to incapacitate their opponents in the Great War. Yet a stick of sodium, when thrust into a tank of chlorine gas, burns brilliantly, forming a substance whose absence from the dining table would lead to protests. The corrosive metal sodium disappears, some of the chlorine (of which one part in 10,000 of air makes breathing painful) also disappears, and in their places we find a white solid which we regularly put into our stomachs. Suppose the sodium chloride turned back into metallic sodium and gaseous chlorine after we had eaten it! Some actions *are* reversible.

From this point it would be easy to launch ourselves upon the

great wide sea of chemistry, to explore the thousands of chemical actions, within and without our bodies, which play so important a role in the processes of life and civilization. But we must not lose sight of our immediate objective. *We are trying to find out what matter is made of, at bottom.* We pause only for a few illustrations to ensure that we are agreed on the meaning of the expression, chemical changes.

A *chemical* change is one in which the composition of the material entering into the action is altered. Matter is transformed into one or more entirely different substances. The rusting of iron, the burning of coal, the bleaching action of hydrogen peroxide, the lighting of a match, the behavior of a sensitive photographic film under the influence of light, the slow combustion of food in our bodies — these are examples of chemical action. A certain substance, or substances, enter into the action, and one or more other substances emerge from the action.

Usually, such transformations can readily be distinguished from *physical* changes. For example, the effect of passing the electric current through a tungsten lamp filament is physical, not chemical. The tungsten is still tungsten, merely hotter than it was before. Similarly, the evaporation of water is a physical change; likewise freezing. The water vapor is still water, chemically speaking, and so is the ice. Gas, liquid or solid, the material is composed of the same elements, hydrogen and oxygen, and in the same proportions. And if some sugar be dissolved in water, the sugar is still there as sugar. It can be detected by taste, it can be recovered by evaporating the water away. Thus this is a physical change, not chemical.

Three Chemical Experiments

It was the *proportions by weight* among the different substances entering into a chemical change that first led John Dalton, and through him the world of science, to a knowledge of the atomic constitution of matter. Certain numerical relationships kept cropping up, certain numbers were found to be repeated with amazing consistency in diverse and, superficially at least, unrelated chemical actions. The continual recurrence of these certain simple proportions throughout the range of chemical phenomena sheds so strong a light on the underlying nature of physical reality that we take a few moments to examine the results of several chemical experiments.

1. The Rusting of Iron. Suppose we wet the inner walls of a glass cylinder with water and then coat the entire interior surface with powdered iron. In this experiment we hasten the familiar action of rusting by making it easy for the oxygen of the air to make contact with the particles of iron. Now stand the cylinder upside down in a shallow tray of water. The water seals the mouth of the cylinder and thus traps a certain amount of air in contact with the iron. Watching the water level, we find that it rises slowly but surely inside the jar, until, after several hours, it comes to a permanent standstill at a height approximately one-fifth of the way up the cylinder. Some of the air has disappeared! — and atmospheric pressure pushes water up to take its place. The oxygen, which comprises about one-fifth of the lower atmosphere, has been used up by uniting with iron to form iron rust. If the jar is lifted without admitting fresh air, and a lighted splinter of wood thrust inside, the flame is instantly extinguished, showing that the combustion-supporting component of the air has been removed. And on inspecting the inner coating of iron we discover some reddish particles of rust (ferric oxide).

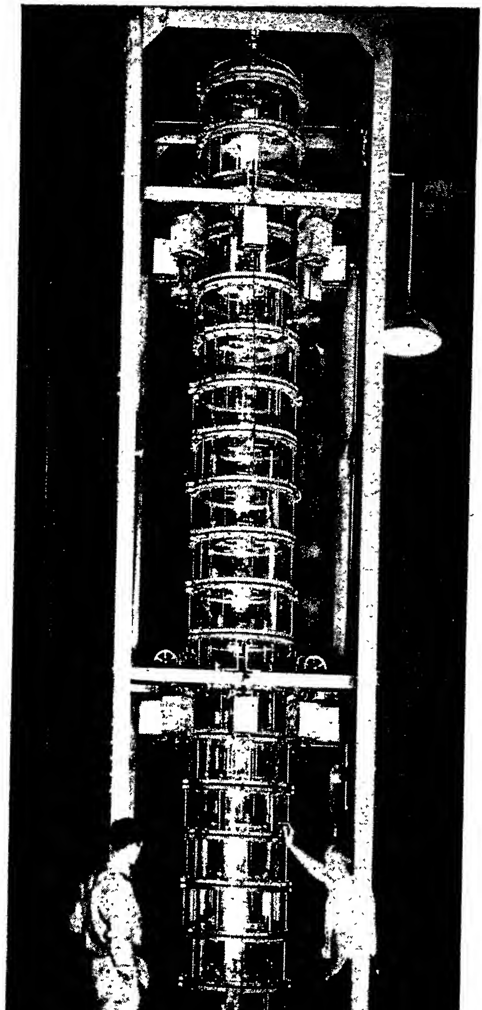


FIGURE 31. An impressive piece of chemical glassware. (Courtesy Corning Glass Works.)

Here is a good example of the type of chemical action known as *combination. Iron plus Oxygen gives Ferric Oxide.* Accurate weighings in hundreds of such experiments show that the rust contains iron and oxygen in certain unvarying proportions. No matter what the actual amount of oxygen used in the experiment, the proportions are always such that if we let the amount of oxygen be represented by 96 parts by weight, the amount of iron is always 223.36 parts, and the amount of rust, or ferric oxide, is always the sum of these two numbers, or 319.36 parts. There is no reason for memorizing numbers unless one expects to use them over and over again, but there is a certain virtue in *seeing* numbers occasionally. They emphasize the fact that the physical sciences rest on a solid foundation of mathematical accuracy. The numbers here may represent tons, pounds, ounces, kilograms, grams, milligrams, or actual atom-weights of oxygen. It is the proportions that count. If we put in an extra amount of one of the reagents, the excess simply does not combine. Regardless of any traps we set for Nature, she goes her way, never fooled, always producing results with the uncanny accuracy of a mathematical wizard who performs marvels of calculation without even writing the problem down.

2. *Iron and Copper Sulphate.* Now we dissolve some crystals of copper sulphate in water. The liquid is blue. No metallic copper is present. Plunge the clean shining blade of a steel knife into the solution. It comes out covered with copper! The blade has now the familiar red-brown color of a copper teapot. For a moment we think we have hit on a wonderfully quick and easy means of copper-plating, but Alas! the copper does not stick tightly to the iron. It rubs off easily. In the solution the copper was combined with sulphur and oxygen. The iron simply pushed the copper aside and took its place. *Iron plus Cupric Sulphate gives Cop-*

per plus Ferrous Sulphate. This sort of action is called *displacement.* In the preceding experiment, some iron combined with oxygen and so disappeared as iron. Here, iron combines with an oxygen-sulphur unit, and metallic copper appears in its place. Weighings would show the same *law of definite proportions* applying here as in the preceding experiment. The numbers would be different, but the fact of definite proportions, or constant composition, would stand out clearly.

3. Calcium and Water. As the next experiment, drop a lump of the silvery white metal calcium into a tray of water, and invert a glass jar full of water over it without letting the water fall out. Bubbles of gas rising from the calcium push some water out of the jar and remain trapped at the top. Soon we have a jarful of hydrogen—and could easily have an explosion. Hydrogen is the lightest of all the gases and an important ingredient in the mixtures that are manufactured for use as fuel in gas stoves. Despite its inflammability it is still used in European airships of the Zeppelin type. By means of a bent glass tube and a few precautions, we secure a fine stream of hydrogen, and on applying a match to the nozzle find that the gas is inflammable. Furthermore, if we let the hydrogen flame play on a cold surface, say the outside of a jar of cold liquid, we collect water. *The flame is producing water!*

Here we have two chemical actions illustrated. Water, as everybody knows, is H_2O, a compound of hydrogen and oxygen. The calcium displaced some hydrogen from the water, then the heat of the match started the hydrogen to combining with oxygen again, the oxygen of the air this time, to form water again. Thus this third experiment affords a second illustration of both *displacement* and *combination.*

Conservation of Mass

The law of definite proportions applies here, as always; but since we have already stressed that law let us make this latest experiment the occasion of emphasizing two additional characteristics of all chemical changes. In Chapter 6 we made brief mention of Lavoisier's brilliant discovery of the principle of *conservation of mass.* Suppose, in a series of careful weighings, we find the total number of grams of all the original substances (calcium, water, oxygen) that entered into our two present actions, also the total weight of the final products of the reactions (calcium hydroxide and water, plus any hydrogen that is not burned in the flame to make water). We should find that, despite the disappearance of the calcium, despite the mysterious appearance of hydrogen in the jar and water in the flame, the total weight, or mass, of the substances entering into the chemical actions equals the mass of the final products. Just as the total quantity of energy in a closed system remains constant, regardless of any changes that it may undergo, so the matter in our chemical experiments is simply transformed, not destroyed or created. *The total mass remains the same.*

Energy of Chemical Transformations

Further, *energy* transformations are involved in all chemical changes. The heat liberated by the flame when the hydrogen combined with the oxygen of the air merely illustrated in an especially obvious way a basic fact of nature: chemical changes are invariably accompanied by energy changes. Either the chemical action yields free energy, as here, or it causes energy to be absorbed from the surroundings.

At the opening of this chapter we raised the question: Is matter something that has energy, or is energy something that has matter? This question, far-fetched though it may have sounded to the reader, now seems to be leading us somewhere. We see that energy and matter are intimately related. Chemical actions which produce heat are called *exothermic;* those that absorb heat, *endothermic*. The combustion of coal, for example, an exothermic reaction, yields from 1,500,000 to 3,800,000 calories per pound of coal, depending on the quality of the coal. This is enough heat to warm from 16 to 40 quarts of liquid water from ice-cold to boiling, under standard conditions. Another interesting example of exothermic action is found in the centuries-old Dutch method of making white lead for painters. The fermentation of tanbark furnishes not only the carbon dioxide needed in the reaction, but also the *heat* required to vaporize acetic acid. (Acetic acid is the characteristic ingredient of vinegar.)

On the other hand, the union of carbon and sulphur to form carbon disulphide, a poisonous insecticide to be used in our next experiment, is endothermic, *absorbing* 171,300 calories of heat for every pound of carbon disulphide that is formed.

Other forms of energy are also involved in many reactions. Witness the kinetic energy acquired by the debris sent hurtling towards the sky when dynamite and trinitrotoluene (TNT) undergo their best-known reactions; the absorption of light energy by the chemical action of photography; the liberation of light energy by a firefly; the electric energy produced by the chemical action that goes on in flashlight cells and automobile storage batteries.

We have already laid great stress on the physical principle of conservation of energy; but the plain fact is, that this great law does not hold when chemical transformations occur *unless that myste-*

rious sort of energy known as chemical energy be taken into account. Physics, broadly speaking, deals with transformations of energy; chemistry, with transformations of matter — but the physicist's most fundamental principle, the law of conservation of energy, holds true only if the energy of any chemical changes be included in the calculations; and, as hinted hitherto without explanation, the chemist's rock-bottom principle, conservation of mass, though accurate enough for all ordinary work, has recently been found to be not rigorously complete unless energy transformations be taken into account. More of this later; but again we see how fruitless it would be to attempt to discover the true nature of physical reality by restricting our attention to either physics or chemistry alone. The truth is, these two sciences complement each other. Neither is complete without the other.

Summary: Some Basic Chemical Ideas

By this time the reader, even if he brings no previous knowledge to the reading, has doubtless begun to think chemically. We have mentioned numerous substances, witnessed several chemical reactions; but we confess freely that our chief objective here is to impress the chemical way of looking at things. A little time is needed to gain this point of view; but once acquired, it never leaves us. To summarize briefly: We have distinguished between *physical* and *chemical* transformations, between *elements* and *compounds.* The fundamental principles of *conservation of mass* and *definite proportions* have been emphasized. Two of the general types of chemical action, *combination* and *displacement,* have been illustrated. The intimate relation of *energy* and *matter* has been pointed out. Now let us quickly extend the range of our illustra-

tive reactions, acquiring several additional ideas *en route,* and then pass on to consider what these basic facts reveal about the structure of matter.

Three Additional Chemical Experiments

1. Iron and Sulphur. Here we suspend a tube of iron filings by a wire and bring a magnet near it. The tube, as expected, swings towards the magnet, showing that iron responds to magnetic force. Trying the same test with a tube of sulphur, a pale yellow solid mined chiefly in Sicily, Texas and Louisiana, we discover that sulphur is not magnetic. The tube is not attracted.

Now, after grinding the iron and sulphur together and suspending as before, we repeat our magnetic test. The tube swings. The iron is still present as iron. We have a mixture, not a compound. The particles of iron, with some sulphur clinging to them, can be pulled out with the magnet and washed with carbon disulphide, an evil-smelling liquid that dissolves sulphur. The dissolved sulphur can be reclaimed by cautiously evaporating away this highly inflammable and poisonous solvent. Thus we find the difference between a mixture and a compound. The ingredients of a *mixture* can be separated by physical means, without chemical action. Also, a mixture may contain the ingredients in almost any proportions; it is not restricted to certain definite proportions, as compounds are.

But suppose we apply heat to a tube of well-mixed iron and sulphur. The burner is needed only to start the action. Soon a violent change takes place, a glow spreads through the entire mass. A large amount of heat is produced, and when the action is over we discover a black, brittle, porous solid in the tube — a substance which neither dissolves in carbon disulphide nor responds to mag-

netic action. No iron has left the tube; yet the failure of the new contents to respond to the magnet shows conclusively that the iron has ceased to exist as iron. The product is ferrous sulphide. *Before* the action the suspended tube remains pulled to one side by the influence of the magnet; but as the iron disappears into combination with the sulphur the tube swings down, its contents grown suddenly indifferent to the magnet's power of attraction. Few simple experiments display more strikingly the amazing thoroughness of chemical transformations. Small wonder that the medieval alchemists cast a glamour of magic around their manipulations, when such transformations as this are possible!

It should be noted that the amount of heat evolved in such an action is as definitely related to the amounts of the reacting substances as those substances are to each other. In a sense, the equation *Iron plus Sulphur gives Ferrous Sulphide,* which may be abbreviated to $Fe + S \rightarrow FeS$, is incomplete. A statement giving the proportions of both the materials and the heat describes the reaction more accurately. Thus:

$$\text{Fe (55.84 gms.)} + \text{S (32.06 gms.)} \rightarrow \text{FeS (87.90 gms.)} + 23{,}060 \text{ calories}$$

Multiply *all* of those numbers by 2, or 7, or 1,000,000, or 0.000001, or by any number you choose except one so unreasonably small as to involve the subdivision of an atom, and the equation will still be true. It is the proportions that count! The reason why chemists prefer one certain set of numbers with which to express these proportions will be explained as soon as we have acquired the right to speak of atoms in these pages.

2. *Decomposition of Mercuric Oxide.* August 1, 1774, Joseph Priestley performed an historic experiment. Heating the red oxide of mercury by concentrating sunlight on it with a lens, or

burning glass, he obtained oxygen — an element essential to all life and so abundant, indeed the most plentiful element known, that it constitutes nearly as large a percentage of the earth's crust as all the other 91 elements put together. Priestley shares the honor of discovering oxygen with a number of other chemists; for the artificial preparation of oxygen and its recognition as a true element identical with the combustion-supporting component of the atmosphere was not one single brilliant stroke in sudden conquest of the unknown, but rather a gradual evolution extending over a century or more.

Priestley, laboring under the errors of the phlogiston hypothesis, named the gas dephlogisticated air; and it remained for Lavoisier, French founder of modern chemistry, discoverer of conservation of mass, dethroner of phlogiston, to give the gas its present name, oxygen. The two men are curiously linked in misfortune. Priestley's sympathy with the ideas of the French Revolution, the movement that guillotined Lavoisier, was one of the causes leading to the destruction of Priestley's home and laboratory by mob action in England on July 14, 1791. Priestley emigrated to America in 1794, the same year that witnessed the execution of Lavoisier.

Repeating Priestley's experiment with a more convenient heating apparatus, we heat a tube of mercuric oxide, the red rust of mercury, and catch the oxygen by means of a bent tube and an inverted jar of water. A glowing wooden splinter thrust into a jar of this pure oxygen blazes up. A bundle of fine iron wires, one end covered with a little burning sulphur to start the action, burns brilliantly in another jar of pure oxygen. The iron is rapidly consumed — burned up. Oil or grease dropped into another jar of oxygen can cause a serious explosion.

Examining the tube in which the mercuric oxide is being heated, we note the shining liquid metal mercury, the quicksilver of the

ancients, forming a mirror-like deposit on the inner walls. To demonstrate that a metal is being formed in the tube, let us use a simple conductivity-tester, a double-pointed "pencil" with two stiff wires in place of the usual writing lead. The two stiff wires are so connected that when both points make contact with a conductor of electricity, an external circuit is closed and a bell rings, or a lamp lights. Thrusting the pencil into some of the original mercuric oxide, we find that the oxide is not a conductor of electricity; but on testing the mercury globules on the inner walls after the action has gone on for a while, we hear the bell ring out to assure us that a true chemical transformation has occurred. In place of the red, non-conducting mercuric oxide we now have new-born mercury, a fairly good conductor of electricity, and also some oxygen, which in this pure state supports and promotes combustion far more vigorously than does the diluted oxygen of the air.

Note, in passing, that we have here an example of a third general type of chemical action. *Combination* and *displacement* have already been illustrated. Now we have *decomposition,* which is just the reverse of combination. Under the influence of the high temperature, the mercuric oxide decomposes, splitting cleanly into its two constituents, mercury and oxygen.

3. Copper and Chlorine. Finally, lest we gain the impression that oxygen is the sole supporter of combustion, let us watch what happens when we drop a very thin leaf of copper, such as is often used in gilding, into a jar of chlorine gas. The copper bursts into flame, burning up rapidly without benefit of either oxygen or a lighted match. A fog of solid cupric chloride, the product of the combination, fills the jar.

Great Names in Chemistry

Except for Priestley's experiment, we have selected our chemical illustrations without regard to historical importance. What we have been trying to do is to gain a preliminary insight into the general characteristics of chemical action by the most direct route possible. We are now ready to confront the problem of the structure of matter as it was faced by three great chemists — Dalton, Berzelius, Avogadro — and thus witness the founding of man's knowledge of the atomic constitution of matter.

Many notables who helped to bring chemistry to the point where John Dalton could do his work have appeared in our pages. Recapitulating briefly, in chronological order by birth dates, we remind ourselves of those names already mentioned: Zosimos, Geber, Razi, Avicenna, Albertus Magnus, Roger Bacon, Basil Valentine, Georgius Agricola, Paracelsus, Robert Boyle, Joseph Black, Henry Cavendish, Joseph Priestley, Antoine Lavoisier. The index will help the reader to bring together the scattered references to these men and to note again their relation to other great figures in the history of thought and action. From first to last of the men listed, the dates range from about 300 A.D. to the time of the French Revolution, some fifteen centuries. Zosimos of Egypt provides a convenient landmark between chemistry as an art and chemistry as alchemy. The alchemical school of thought lasted until the time of Boyle; although we should note that for a century and a half preceding Boyle's distinction between elements and compounds the importance of alchemical ideas had been subordinated to the *iatrochemical* point of view, first effectively stressed by Paracelsus. Paracelsus insisted that the first duty of chemistry was to prepare pure medicines and discover new ones. Despite many errors (he thought man was composed of salt, sul-

phur, and mercury) he energetically goaded his contemporaries towards useful study, and he himself gave the medical world laudanum (tincture of opium). Chemistry as an art; as alchemy; as aid-in-chief to the physician (iatrochemistry); and, finally, chemistry as an independent science — these are the steps in the evolution of this indispensable branch of human knowledge.

The chronological list of names given above is by no means complete. Other important chemists who antedated Dalton will be discovered by the reader who takes time to delve into the history of chemistry. Johann van Helmont and Johann Rudolf Glauber, two iatrochemists who speeded the work, came between Paracelsus and Boyle. Johann Becher (1635–1682), John Mayow, Georg Ernst Stahl, Hermann Boerhaave, Stephen Hales, Guillaume Rouelle, in chronological order as named, made notable the interval between Boyle and Joseph Black. Van Helmont invented the word *gas,* stressed the importance of gases as a distinct class of substances, and devised the pneumatic trough method of trapping gases which we applied in collecting our oxygen and hydrogen over water. The role that inventions of new apparatus and methods of manipulation play in scientific discovery is often underestimated. A gas has first to be caught before it can be identified — at least unless we call in the modern spectroscope. And consider, for example, the Benedictine monk Dom Pérignon, born 1638, whose twin inventions, champagne and cork stoppers for bottles, might easily be placed in the wrong order of importance. We leave to the reader the fascinating project of selecting any conspicuous laboratory article or device, no matter how simple, and tracing its evolution and influence. Returning to our list, we note that a century before Priestley discovered oxygen, John Mayow recognized the existence of a specific combustion-supporting component of the atmosphere, named it *igneo-aereus,* and measured

what fraction of the air it composed. Hales studied (we give the modern names) hydrogen, carbon monoxide, carbon dioxide, sulphur dioxide, and methane (marsh gas). Johann Becher and Georg Stahl founded the famous phlogiston hypothesis, which we considered at some length in dealing with caloric and other fictitious imponderables invented by man. Becher's *terra pinguis,* or fatty earth, became the phlogiston of Stahl. And Karl Wilhelm Scheele, whose brief life was overlapped by that of Priestley at both ends, first isolated chlorine, discovered more than a dozen new acids, proved graphite to be a form of carbon, and in general contributed greatly to the increase of experimental knowledge of chemistry, though not much given to theoretical pioneering.

It would be interesting to select one of these characters at random, study him thoroughly, write an essay on him. Perhaps the reader will do it. Suppose Henry Cavendish (1731–1810) were chosen. This is the same wealthy, almost pathologically bashful English aristocrat who first determined the constant of gravitation in Newton's law and thus " weighed " the earth, and who also discovered the composition of water by making water out of hydrogen and oxygen gases, exploding the mixture in a glass flask with the aid of an electric spark. He determined the composition of nitric acid by synthesizing it; discovered hydrogen (though Lavoisier named it); anticipated Coulomb by a decade in the discovery of Coulomb's law of electric attraction; and proved by experiment that slightly less than one per cent of the air consists of neither oxygen nor nitrogen. This atmospheric residue, mostly argon, was not identified until nearly a century after his death. To read widely on one such character, to become an authority on his scientific ideas, the apparatus he used, his religion, politics, diet, friends, personal habits, the thought and customs of his generation and the influence of his discoveries; perhaps repeat his experi-

ments; in short, to *become* that person occasionally as nearly as an instructed imagination permits — so one could gain a fruitful and lasting hobby. Knowledge for its own sake, though sometimes derided, has its charms.

Discoverers of Atoms

But enough! We see that Boyle, when he defined an element, and Dalton, Berzelius and Avogadro, when they made the fundamental advance which we are now to consider, were not lone thinkers operating in an intellectual desert. Perhaps no single bit of data reveals more strikingly the strides that followed Boyle's definition than the increase in the number of known elements. Nine of the 92, like the five brightest planets, had been known from prehistoric times. In the first thousand-year period of our arbitrary division of the history of science no new element was discovered; during the second thousand years, one was added; in the two and a half centuries from the end of that period to the publication of Boyle's *The Sceptical Chymist* in 1661, another was discovered, making eleven in all — and by the close of the year 1808, in which John Dalton's *A New System of Chemical Philosophy: Part I* appeared, the discovery of *thirty-four* new elements had raised the total to 45, and there were only 47 to go!

Boyle's definition sealed the fate of the four "elements" of Aristotle — fire, air, water, earth — though Stahl's phlogiston was still to arise to lay a plague on science. Lavoisier's discovery of conservation of mass turned chemistry into an exact quantitative science. Now Dalton, Avogadro, and Berzelius, who were, respectively, 28, 18 and 15 years old when Lavoisier went to the guillotine, established the atomic theory that gave chemistry the correct point of view and made inevitable the chemistry of today.

John Dalton, the Quaker schoolmaster of England, a man who at the height of his fame stayed in his humble home teaching arithmetic to small boys while his ideas went abroad to teach chemistry to the world's greatest — Dalton supplied the original ideas and arguments and furnished some reasonably reliable experimental results. Jöns Jakob Berzelius, chemist and baron of Sweden, added the authority of accurate weighings and, guided by Dalton's theory, invented a simple system of writing chemical formulae which disgusted Dalton himself but is familiar to everyone who has looked into a modern chemistry book. Amadeo Avogadro, Count of Quaregna and Cerreto, doctor of jurisprudence, professor of mathematical physics at the University of Turin, removed the last difficulty by finding in the gas law of Gay-Lussac, chemist and peer of France, the one idea needed to complete a true picture.

Once again great men of several countries cooperated to build one structure for the benefit of all mankind. This is the rule, not the exception, in science. In the midst of the Napoleonic wars, from October 1813 until after Waterloo, Sir Humphry Davy, contemporary of Dalton, citizen of Napoleon's inveterate enemy Great Britain, traveled honored and feted throughout France and Italy, receiving the privileges of continental laboratories in many places. That such courtesies to an enemy alien would be impossible today bears witness, as Henry Crew has pointed out, not to a change of heart in humanity, but to the role that science now plays in devising modern engines of destruction.

Foundations of the Atomic Theory

What did Dalton, Berzelius and Avogadro discover that changed atomic theory from a vague hypothesis to firmly established fact? Let us treat these three contemporaries as a group, omitting errors,

and substituting modern chemical names and figures. To receive Dalton's basic idea, one can get himself into the proper frame of mind by considering how financial accounts would look if the sole increments of price were dimes and quarters. The proprietor of a bakery, stopping every evening to examine the charge accounts in the cashier's office, would find certain totals recurring, some never appearing. For instance, 15 cents would never appear, and there would never be a total that was not divisible by 5, say 3, 16, or 37 cents. Our analogy is crude and must not be pressed too far. *Discontinuity* is the idea suggested here. For two kinds of money units, which are here combining in many ways to form charge accounts, substitute 92 kinds of atoms, which combine in many ways to produce the molecules of compounds. The task facing these pioneers in chemical theory was to deduce the *relative* weights of the units of elements, namely the atoms, by studying the proportions in which the elements combined to form compounds.

Here we have an indirect method of investigation comparable to Newton's study of gravitation. Just as Newton found that his law predicted the observed motion of the moon and planets with unfailing accuracy, so Dalton showed that his conception accounted for the three fundamental principles of chemistry that he knew.

1. Conservation of Mass. First, if chemical reactions were merely the rearranging of atoms in different groupings, the total weight of matter would remain unchanged and the known conservation of mass, which Lavoisier had discovered shortly before the American Revolution, would automatically result. To transfer money from one pocket to another does not change the total amount of money attached to one's person. According to the atomic view, a *combination,* say the uniting of iron with sulphur

in our experiment with the magnet, would be merely the joining of atoms of iron with atoms of sulphur to form compound molecules. The *decomposition* of mercuric oxide in Priestley's experiment would consist in separating the atoms of mercury and oxygen which were already combined in compound molecules. In a *displacement,* as when the steel blade emerged from the bath coated with copper, an atom of iron would take the place of a copper atom which was combined with other atoms, thus freeing the copper. Similarly, with other types of reactions. Obviously, a mere shifting around of atoms would account beautifully for the observed fact that the products of a reaction always weigh the same as the original substances.

2. *Law of Definite Proportions.* Second, the atomic view would account for the fact that elements in combining to form compounds always do so in certain definite proportions. Suppose, in our iron-sulphur experiment, that the iron consists of atoms which *are all exactly alike,* that the sulphur consists of atoms which, though different from the iron atoms, are all exactly alike, and that the product of the combination consists of molecules each containing one atom of iron and one of sulphur. Two pounds of the compound product must then contain exactly twice as many atoms of iron as one pound does, but it also contains twice as many atoms of sulphur, hence the *proportions* of iron and sulphur would be the same in two pounds as in one pound.

The same reasoning would apply to other compounds. Water is always found to contain 88.81 percent by weight of oxygen, 11.19 percent of hydrogen. (We are not speaking of heavy water, a different compound.) Wherever the water comes from, and whether we analyze a drop or a bucketful, the proportions of oxygen and hydrogen are always the same. According to Dalton's idea, this proportionality would hold down to the last molecule of

water, so from that proportionality he expected to calculate the relative weights of oxygen and hydrogen atoms. (He had no means of knowing that in water *two* atoms of hydrogen are combined with one of oxygen.) Similar considerations applied to other substances. If every contribution dropped into the collection plate consisted of one dime and one quarter stuck together, then the proportions of dimes and quarters would always be the same, month after month, whether the total collection was good or poor. The dime and the quarter represent atoms, and when stuck together, a molecule — a very simple example in comparison with the great numbers of compounds to which the Daltonian idea must be applied.

3. The Law of Multiple Proportions. Third, Dalton's theory affords a perfect explanation of the results observed when a given pair of elements combine in several different proportions. Here we encounter a series of relationships so striking that, if matter were *not* composed of atoms, these relationships would have to be set down as the most amazing coincidences that one could invent in a week's hard work, not excepting the fantastic results which we considered before dismissing the absurd idea that mere chance was what caused the orbital motion of some 1273 planets and planetoids to take place in the same direction around the sun.

Many pairs of elements combine in more than one proportion. Water, for example, is not the only compound of hydrogen and oxygen. These same elements also form hydrogen peroxide, the well-known bleaching agent and mild germicide, which when not diluted is a thick syrupy liquid that blisters the skin. The difference between water and hydrogen peroxide is due to the fact that the latter contains exactly twice as much oxygen in proportion to hydrogen as does water. Note the expression, *exactly twice.* This means 2.000 times as much, not 2.001, or 1.987, or any other

value. How easy it is to picture one extra whole atom joining in to double the proportion of oxygen. And what an astounding coincidence the exactness of that two-fold ratio would present if matter were continuous, like space and time, so that fractional increases of any magnitude would be possible!

Examples of this striking behavior could be multiplied at great length. We add only the five compounds of nitrogen and oxygen. Perhaps the best-known compound of these two atmospheric gases is nitrous oxide, so-called laughing gas. This colorless, pleasant-smelling gas was discovered by Priestley in 1772. Twenty-seven years later Sir Humphry Davy began his series of scientific triumphs by discovering its exhilarating effect when breathed — an exaltation followed by unconsciousness on prolonged inhalation. Tales of the early uses of the gas in social entertainment, and its subsequent application as an anaesthetic, make interesting reading. But our point here is proportions by weight. Nitrous oxide contains exactly 1.751 grams of nitrogen for every gram of oxygen. Let us find the amounts of oxygen associated with that same amount of nitrogen in the four other compounds of these two elements. As regards the substances themselves, all we need note here is that they exist, and that their composition is always as follows:

Substance	*Amount of Nitrogen* (grams)	*Amount of Oxygen* (grams)
Nitrous Oxide	1.751	1.000
Nitric Oxide	1.751	2.000
Nitrogen Trioxide	1.751	3.000
Nitrogen Tetroxide	1.751	4.000
Nitrogen Pentoxide	1.751	5.000

If the exact doubling of the proportion of oxygen in passing from water to hydrogen peroxide seemed so conclusive a proof of the existence of atoms, what shall we say now, when we find the same sort of evidence repeated over and over again in the case of oxygen and nitrogen? Will anyone have recourse to a doctrine of coincidences? For every 1.751 grams of nitrogen, we can have exactly 1 gram of oxygen, or exactly 2, or 3, or 4, or 5 grams — but no fractional additions! Whole multiples, or nothing! Not 1.001 times; not 1.002 times, or any of the 999 intermediate values between 1 and 2, to the third decimal place. If matter were continuous, not atomic, the odds would be 999 to 1 against finding that first multiple to be exactly 2.000. And what the odds would be against finding all four multiples exact whole numbers *simultaneously,* we shall leave to the mathematically inclined reader. Surely the proof of the existence of atoms was inescapable even before they were detected individually. Dalton himself discovered the law of multiple proportions, four years before he published his epoch-making treatise. We state it here:

Whenever a given fixed quantity of one element can combine with different quantities of a second element, the larger of these different quantities are always exact whole multiples of the smallest amount that will unite with the given quantity of the first.

Continuity Versus Discontinuity

The reader will observe that in developing the discontinuity of matter we are going far beyond the simple results that could be obtained by comparing the weights of a box of bricks and a bucket of water. Such an experiment would exemplify, on a gross scale, the difference between continuity and discontinuity. By adding water drop by drop one could cause the contents of the bucket to

pass continuously through every successive value of weight that one could detect by household methods of weighing; but on adding bricks one would find the weight increasing by jumps, discontinuously. What we are doing here, following Dalton and his colleagues, is to prove that even the water itself, poreless though it appears, is discontinuous at bottom. Relentlessly we are tracking down the different " bricks " of which all matter is composed — and we are to discover not only their *relative* weights, but finally, surpassing Dalton's generation, their actual weights as well, testing them one by one in the marvelous " scales " of modern science. We stress the idea of atomism so thoroughly here, not only because it is fundamental in our knowledge of the underlying nature of material reality and the foundation of chemistry's outwardly prosaic business of making fertilizers from thin air, red rubber sponges from corn, rayon from wood and aspirin from coal — but also because, as we shall see, the ideas of discontinuity or atomism which Dalton proved are found to apply both in the realm of energy and in the sub-atomic strata of electricity. Once this atomic idea is established with crystal clarity, we can shift the clutch to high. In study, as in the progress of science itself, the more we learn the faster we can go. One sound idea begets a headful.

Short of actually counting atoms, which even today can be done directly only in certain cases, the Daltonian idea could be verified only by the cumulative weight of rather large masses of data. We complete our survey of this significant development by extending our study to several representative compounds of five familiar elements.

Five Elements and Seven Compounds

The five elements of our concluding illustration are hydrogen, carbon, oxygen, sodium and chlorine. The chemical symbols of

atoms of these elements are, respectively, H, C, O, Na, Cl. Four of these are already familiar to the reader, as a result of frequent references to them. The remaining element, carbon, is seen as chimney soot, lampblack, graphite, charcoal, and the black residue obtained when sugar is charred. Diamonds, being nearly pure crystal carbon, burn. Living organisms are so largely composed of carbon in combination with other elements that the study of carbon compounds is called organic chemistry.

Three of the representative compounds of these elements which we select for our illustration have already been referred to: *Water* (H_2O); *Hydrogen Peroxide* (H_2O_2); and *Sodium Chloride* (NaCl), or table salt. The other compounds which we have in mind are: *Carbon Monoxide* (CO), an odorless, colorless, tasteless but deadly gas present in the exhausts of automobiles; *Carbon Dioxide* (CO_2) one of the rarer components of the atmosphere, important in plant growth, exhaled by man and other animals; *Hydrogen Chloride* (HCl), which when dissolved in water forms hydrochloric acid, a liquid widely used in industry and present in small quantities as an important component of the gastric juices; *Sodium Hydroxide* (NaOH), also called caustic soda, a strong alkali or base that gives a slippery feeling to water and is used in the manufacture of soap.

Matter Is Atomic

These seven compounds illustrate beautifully the remarkable facts of proportions which Dalton stressed. He would have been very happy indeed if he had had data as accurate as those which we are using. In stating the proportions, we do not imply that all one needs to do to obtain the compound is to mix the elements in the proportions given. Special methods are often needed. The hydrogen and oxygen would unite to form water if we passed an

electric spark through the mixture, as Cavendish did in investigating the composition of water. The carbon dioxide could be formed by burning either solid carbon or gaseous carbon monoxide in air. The hydrochloric acid could be decomposed into hydrogen and chlorine by passing an electric current through the solution. What we give below are the proportions of the elements always found in the compounds, regardless of the methods of analysis used. Pounds, grams or any other units of weight would fit the numbers; but we merely say *units,* because the proportions by weight are obviously the same no matter what units are employed.

(1) 18.016 units of H_2O contain 2.016 units of Hydrogen and 16.000 units of Oxygen.

(2) 17.008 units of H_2O_2 contain 1.008 units of Hydrogen and 16.000 units of Oxygen.

(3) 28.000 units of CO contain 12.000 units of Carbon and 16.000 units of Oxygen.

(4) 22.000 units of CO_2 contain 6.000 units of Carbon and 16.000 units of Oxygen.

(5) 36.465 units of HCl contain 1.008 units of Hydrogen and 35.457 units of Chlorine.

(6) 58.454 units of NaCl contain 22.997 units of Sodium and 35.457 units of Chlorine.

(7) 40.005 units of NaOH contain 22.997 units of Sodium and 16.000 units of Oxygen and 1.008 units of Hydrogen.

Except for the 16 units of oxygen, an amount which we chose arbitrarily in order to prevent the value for hydrogen, which has the smallest atomic weight (see appendix) of all the elements, from being less than 1, the repetitions of certain numbers in the table are especially revealing. In Item 2, a certain amount of hydrogen is joined with the 16 units of oxygen in hydrogen peroxide. In Item 5, that same amount of hydrogen is found united with a cer-

tain weight of chlorine. In Item 6, exactly that same weight of chlorine is joined with a stated weight of sodium in sodium chloride. Finally, in Item 7, that same stated amount of sodium is found combined with the *original amounts* of oxygen and hydrogen. The agreement is exact, not approximate. *Why should the relative proportions of oxygen and hydrogen in caustic soda be exactly the same as in the bleaching agent hydrogen peroxide?* One is irresistibly drawn to the conclusion that whole atoms are joining with whole atoms, and that *in-between proportions are simply not available in nature.* And if we expanded our seven-item table to thousands of lines, one for every known compound, the same fact (except for a few *isotopes* to be considered later) would stand out throughout that enormous mass of data. On such a foundation rests the atomic theory, a solid monument to the genius of the pioneers and to the patient toil of the thousands of workers who through the decades have amassed the impressive volume of quantitative evidence.

Additional conclusions of great interest can be drawn from our seven-item illustration of chemical behavior. Comparing Items 2, 5, and 7, we notice that 1.008 units of hydrogen is an amount that fits into the proportions based on 16 units of oxygen; but Item 1 shows that exactly twice that quantity of hydrogen is also consistent with the system. Items 3 and 4 reveal another example of this significant property of matter. Either 6 units of carbon, or exactly twice that amount, namely 12, are also consistent with 16 units of oxygen. If the persistent recurrence of certain definite proportions be accepted as proof of the atomic nature of matter—an inescapable conclusion—then the additional fact just pointed out shows that *more than one atom of an element may act as a unit.* In such cases, as already pointed out, the proportions found by experiment are always small whole multiples—exactly 1, 2, 3, 4,

etc. — of certain basic quantities. The absence of fractions reinforces the idea that chemical actions involve the interchange of atoms. If matter were continuous, fractional increases would be the rule, and whole multiples so rare as to be almost non-existent.

Of course what we have said seems obvious when one looks at the chemical formulae — H_2O, H_2O_2, CO, etc. — for these show the number of atoms of each element that are joined to make one molecule of the compound; but the reader should remember that these convenient and revealing formulae came *after,* not before, the establishing of the atomic view. They are results of the theory, not the original evidence. To cite one instance, Dalton thought that water was what we should now write HO, and not until Avogadro contributed a certain idea was the difficulty surmounted.

Avogadro's View of Molecules

The final perfecting of the theory resulted from an idea that was suggested to Avogadro by the results of Gay-Lussac's experimental studies of the volumes of gases that entered into given combinations. Heretofore we have been dealing with weights, not volumes. Of course the volume of a given weight of gas may be almost anything we please. We can squeeze a pound of oxygen into a stout quart jar, or let it expand to fill a cathedral. For this reason, when we speak of the proportions of the volumes of gas entering into a chemical union, we always understand that the gases are under the same pressure and equally warm. With this agreement, let us quickly see what the facts about volumes can add to atomic theory.

First, the almost unlimited compressibility of a permanent gas strongly suggests that the molecules are normally very far apart. The space that is actually filled by molecules must be exceedingly

small in comparison with the great quantities of open space between molecules. If this be the case, Avogadro reasoned, the actual size of each molecule may be negligible in determining the total volume to be occupied by the gas. Some other property of the molecule must determine how much space there needs to be per molecule at a given pressure and temperature.

Avogadro saw that this idea would account perfectly for some queer facts of the proportions of gases by volumes. For example, *two* volumes of carbon monoxide combine with *one* volume of oxygen to give *two* volumes of carbon dioxide. By volume measure, the added oxygen seems to disappear! Suppose, said Avogadro, that at any given temperature and pressure, *every gas contains the same number of molecules per unit volume as every other gas.* Then in *two* cubic feet of carbon dioxide there would be *twice* as many molecules as in *one* cubic foot of oxygen, and to give every carbon monoxide molecule some extra oxygen, every molecule of oxygen would have to divide itself into two. The idea is as simple as dividing twenty pieces of candy among forty children. There would now be the same number of molecules of carbon dioxide as there were originally of carbon monoxide, and the total volume would not be increased, which agrees with the experimental result. Therefore the oxygen, since each molecule split into two, must originally have consisted not of single atoms, but of molecules each containing two atoms of oxygen. This would precisely account for the apparent disappearance of the oxygen in the reaction, so far as space occupied is concerned.

Here was the idea which rescued Dalton's theory from uncertainties so serious that Dalton himself predicted they could never be rectified. The proportions *by weight* of the elements in compounds revealed the relative *atomic* weights of the elements (see appendix) — and Gay-Lussac's law of the combining proportions

of gases *by volume,* together with Avogadro's idea, enabled scientists to determine the relative weights of the *molecules* of all substances that could be studied as gases or vapors. The molecules of oxygen, chlorine, and hydrogen, for example, each consist of two atoms, and so are written O_2, Cl_2, H_2. Further, by comparing the weight of a standard volume of gaseous water (steam) with the weights of equal volumes of hydrogen gas and oxygen gas, one readily proves that water is H_2O; not HO as Dalton believed. By such checking and counter-checking, ambiguities are removed, errors corrected.

Molecules and Atoms: Numbers and Masses

Today a great mass of evidence has accumulated to support Avogadro's famous hypothesis. The agreement of new results, predicted by this view, with the experimental findings, affords ample confirmation. It may be considered as proved that under the same conditions of pressure and temperature, equal volumes of all gases do indeed contain equal numbers of molecules. The number is 443×10^{18} molecules per cubic inch — 443 billion billions of them — at one atmosphere of pressure and the temperature of melting ice. *The weights of individual molecules of two different gases are therefore proportional to the weights of equal volumes of those two gases.* At the pressure and temperature stated above, air weighs 0.0807 pounds per cubic foot, oxygen 0.0892, hydrogen 0.00561, nitrogen 0.0781. One atom of hydrogen weighs 1.6617×10^{-24} grams, a molecule twice as much. One atom of oxygen weighs 25.82×10^{-24} grams, a molecule twice as much. Thus the weights (or masses) of compound molecules can be found. Add the masses of two atoms of hydrogen and one of oxygen to find how much a molecule of water weighs. The result, written out

to show how small it is, is 0.0000000000000000000000000642 pounds. Weigh enough water to fill a cup, divide by that number, and you will learn how many molecules the cupful of water contains. The result is so large that there is no use trying to imagine it. A person endowed with perpetual youth and an undying passion for counting at top speed twenty-four hours a day could be only nicely started toward that number if he had begun counting when the earth was formed, one to eight billion years ago. Molecules and atoms are almost inconceivably small and numerous; yet as we shall presently see, in certain instances scientists have succeeded in dealing with them *individually*.

Summing up, let us conclude that elements are composed of molecules, each molecule consisting of one or more atoms of the element; and that compounds are composed of molecules which contain, in the simplest case, one atom of each of two elements, as in table salt, but may contain many atoms. The molecule of cane sugar, for example, contains 12 atoms of carbon, 22 atoms of hydrogen, and 11 atoms of oxygen. The formula is $C_{12}H_{22}O_{11}$.

Thus, thanks to Dalton, Berzelius, Avogadro and others, the chemist writes his neat formulae, each showing how many atoms of different kinds go to form a molecule of a given compound. He writes these for thousands of compounds, he works by barter and exchange in forming new compounds. By long decades of study he has learned very well indeed which atoms will be readily accepted as legal tender by certain types of molecules, which will be unconditionally rejected, and which ones can be forced on an unwilling molecule by dint of high temperatures or electricity, or by the good offices of an accommodating intermediary. To stand in a simple chemical laboratory such as those early-nineteenth-century workers used, to see the shelves sparsely filled with the boxes and bottles of raw materials in bulk — materials that suc-

ceed so well in hiding their atoms and molecules from the human eye — to see a stove, a sink, a chemical balance, a little glassware, and then to re-read our brief development of atomic theory, and perhaps glance at the accurate tables of atomic weights to be found in the appendix, is to realize vividly that the atomic theory of today was not an automatic development, not something to be taken for granted. It was proved by measurements, but no amount of measuring, however painstaking, can be a substitute for thinking. Many eyes have seen the signs written on the pages of nature; a few have read them.

Chapter 8

THE NATURE OF HEAT

THE way was now open to the solution of a mystery which our study of heat left unsolved. Joule had proved that heat is energy — but what kind of energy is it? Avogadro's clear conception of a gas as a collection of widely spaced molecules, all equally numerous (in equal volumes) regardless of the chemical identity of the gas, was ready to be combined with Joule's proof that heat is energy. Joule himself did it, in a paper read eight years before the great Italian died. How recently these developments have come may be judged by the fact that Avogadro's death did not occur until five years before the beginning of the American Civil War. Without distinguishing between the contributions of Joule and those of his eminent successors (and predecessors; for the idea that heat is a mode of motion was not new) let us quickly examine the kinetic theory of the nature of heat.

Is Heat Kinetic Energy?

If heat is energy, as Joule proved, what was more natural than to consider it to be the kinetic energy of the molecules of which matter was now known to be composed? Suppose the molecules are incessantly moving at high speeds. A falling stone has kinetic energy. A molecule would have kinetic energy if in motion. Friction, to mention one method of heating a body, involves motion. Why should the friction not stir up the invisible molecules, as Count Rumford suggested, making them move faster and thus

transferring some of the energy of the large moving bodies to the molecules which compose them?

There is the basic idea of the kinetic theory of heat. At the start, before analyzing the evidence, all one can say is that it seems reasonable. It accounts for the fact that friction and impact produce heat. It does no violence to the law of conservation of energy — in fact, it helps to explain that law. It leads one to expect gases to exert an outward pressure if they are shut up, as in tires, due to their impacts against the inner walls — and they do. The same picture of gases as swarms of swiftly flying molecules would explain the ease and speed with which the vapor from the boiling coffee brings the fragrant aroma from the kitchen to your chair in the living room. It accounts for the ability of gases to occupy the same space at the same time. One would also expect the Brownian movement, the erratic dancing of microscopic particles that are small enough to respond noticeably to the unequal bombardments of molecules against two opposite sides. Robert Brown, an English botanist, discovered such a movement in 1827; it can readily be seen by looking through a good microscope at well-lighted particles of smoke suspended in the air.

Gas Molecules and Tennis Balls

Further, if heat is the energy of moving molecules, a gas would be expected to cool itself when it pushes a piston and does work, as in a heat engine. This cooling, already obvious as a consequence of conservation of energy, would then be explained. This is easy to see. Suppose you stand tossing tennis balls against a door. If the door is locked, the ball rebounds with virtually unchanged speed; but if the door is free to swing, it yields a little when the tennis ball strikes it, and the ball rebounds with lessened velocity.

Part of the ball's energy of motion has been imparted to the door. Turning to molecules, we see that if moving molecules of hot gas in a cylinder are pushing a movable piston, they will rebound with lessened speed if the piston recedes under their combined impacts. Hence the gas molecules will have given some of their kinetic energy to the piston and — if heat is the energy of molecular motion — the gas will be cooled. This effect is well known. A gas can be cooled to the liquefying point, even frozen, by making it do work at the expense of its own heat energy.

Conversely, if the piston is forced down so as to squeeze the gas into a smaller space, the molecules will gain speed every time they rebound from the piston, just as a tennis ball will rebound faster than it struck if the door is slammed against it at the moment of impact. Thus compressing a gas, doing work on it, will make the molecules move faster and, if heat is molecular kinetic energy, the gas will be warmed. Anyone who has used a tire pump vigorously knows that it gets very warm.

So far, so good. The idea sounds reasonable. It explains many effects which otherwise would go unexplained. But we have come far enough to know that science sees a great difference between sounding reasonable and being proved. The atomic theory seemed reasonable very early, but it was not accepted until a great mass of quantitative evidence had been accumulated which not only agreed precisely with the atomic picture but could not be explained by any other view. Just so with the kinetic theory of heat. It has successfully met quantitative tests too numerous to mention here. Let us content ourselves with one analysis, dealing with the pressures of gases. In subjecting the kinetic theory of heat to the rigorous test provided by the exact laws of gases which Robert Boyle and Jacques Charles discovered we are following a path suggested by Joule, the chief founder of the principle of conserva-

tion of energy; for this was the subject of his famous paper in 1848. One hundred and ten years earlier, however, Daniel Bernoulli had explained gas pressures in terms of invisible, moving particles — though with no reference to the nature of heat.

A Chaos of Molecular Motion

Now put a hollow tin box on the table before you. There is no need to call in the sheet metal worker: the imagination suffices. The box is a cube, each edge exactly 1 foot long. That is about the length of an adult's forearm, from elbow to knuckles. Within the box is a swarm of invisible air molecules. How numerous they are may be inferred from the data given above, and we are now to picture them as moving swiftly in all directions, colliding with one another and with the inner walls of the box. We are assuming the truth of the kinetic theory to see if it predicts a true result. There is a perfect chaos of motion. Let us suppose that the molecules are perfectly elastic, so that there is no net loss of kinetic energy when collision occurs, merely a change in the direction of motion. Therefore the collisions of molecule with molecule do not affect our problem. We need deal only with the impacts against the walls. We want to find out how great a pressure the molecules exert on the walls.

Concentrate attention on the front wall of the box, the wall facing us. At any instant only a few molecules will be approaching this wall perpendicularly. Most of the molecules will strike it obliquely, rebound at an angle, and strike other walls. But the total quantity of motion, or momentum, within the box is the same as it would be if a third of the molecules were moving directly back and forth from front to back, a third from left to right, a third directly up and down. We shall not take time to prove this now:

the fact has been established by studies of motion in numerous cases in which no hypotheses concerning molecules were involved.

Pressure Caused by Molecular Motion

How many times will a representative molecule strike the front wall in one second? The molecule has a certain velocity, which may as well be the average velocity. Velocity is the number of feet traveled per second. But between impacts the molecule must travel from the front wall to the rear, and back again — a distance of two feet. If it travels a certain number of feet per second, it will travel half that many two-foot units in a second. Therefore the number of times one molecule strikes the front wall in one second equals one-half its velocity, or $\frac{1}{2}$V.

Change of Momentum per Second. In a former section we learned that the force exerted by a moving body equals the rate of change of its momentum, and we applied that fact to the catching of a ball, to dancing on tile floors, to several problems. Since we want to find the force exerted on the front wall of our box, let us calculate the molecule's rate of change of momentum.

The momentum of a moving body equals its mass multiplied by its velocity, or mV. Therefore the momentum changes when the velocity changes. Just before striking the front wall, the molecule has a certain momentum *towards* the wall. At impact this momentum is temporarily reduced to zero — a change equal to the whole momentum — and an instant later the molecule is moving *away* from the wall with a momentum equal to its original value. Thus the total change of momentum at one impact is *twice* the average momentum, or 2mV. The change of momentum in a whole second will be the change per impact multiplied by the number of impacts per second, or 2mV times $\frac{1}{2}$V, which gives

us mV^2. This is for one molecule, and we saw that one-third of the total number of molecules in the box, or ⅓ N, may be considered to be undergoing this change of momentum at the front wall every second. Therefore the whole change of momentum at the front wall in one second equals ⅓ NmV^2. But Nm is obviously the whole mass of gas in the box; for the total mass must equal the mass of one molecule multiplied by the number of molecules. So put the total mass of the gas, say M, in place of Nm, and we see that the rate of change of momentum, which is equal to the force exerted by the flying molecules on the wall of the box, is equal to ⅓ MV^2.

Kinetic Energy. Does not that quantity MV^2 sound familiar? In our study of energy we learned that the kinetic energy of moving matter equals one-half of the mass multiplied by the square of the velocity. Therefore MV^2, without the half, equals twice the kinetic energy of the moving molecules in our box, and one-third of twice the kinetic energy is two-thirds. What we have found is that the force produced by the molecular bombardment on our 1 square foot of wall area, or the *pressure,* equals two-thirds of the kinetic energy of the molecules. (Pressure is merely the force *per unit area.*)

The full meaning of this interesting result will appear to better advantage if we do not limit ourselves to exactly 1 cubic foot of molecules. Suppose the box had been 2, or 7, or any number of feet along one edge, say L feet. Then the number of impacts per second would have been reduced by the factor L, since the molecules would have had to travel L times as far between impacts. Also, the impacts would have been spread over an area of L^2 square feet, instead of 1 sq. ft., and the number per sq. ft., on which the *pressure* depends, would have been reduced by the factor L^2. The net result would be to divide the right-hand side of our equality

by $L \times L^2$, or L^3, which is exactly equal to the volume of the box. And to divide the right side by the volume is equivalent to multiplying the left side by the volume. Thus we can state a general result: *The pressure of the gas times its volume equals two-thirds of the total kinetic energy of the moving molecules.*

Heat Is *Kinetic*

But what did we find Boyle's experimental law to be? That same product, the pressure times the volume, is constant so long as the temperature of the gas remains constant. Evidently the result which we have just deduced by assuming the kinetic theory agrees perfectly with Boyle's experimental findings *provided the temperature of the gas is proportional to the kinetic energy of the molecules.* That was precisely the issue we started with. We have found that the kinetic energy of the moving molecules must remain unchanged if the *temperature* is to stay the same. What could be clearer? And to raise the temperature of a body, as by adding heat, we must increase the kinetic energy of the molecules.

Absolute Zero of Temperature

It would be interesting to pursue the argument farther, but we cannot take much of the reader's time for intricate analyses. We have too large a field to cover. Suffice it to say that temperature, which until now in our pages has meant little more than the reading of the mercury on a scale that Fahrenheit chose arbitrarily in 1714, assumes a true physical reality. It is measured by the kinetic energy of the moving molecules. As soon as we supplement our findings with the aid of Charles' law of the effect of temperature-changes on the pressure and volume of a gas, we find that at 273

degrees below zero on the centigrade scale the molecules would be at rest. They would not be moving; they could not be slowed down any more; the material would be absolutely cold. It could not be made any colder, for it would have no more heat energy to lose. For many purposes scientists find it convenient to know the whole temperature of a body, which is the temperature on the centigrade scale plus 273, or the temperature on the Fahrenheit scale plus 459.4 degrees. Temperatures measured from the absolute zero are called absolute temperatures.

The absolute temperature of melting ice is 273, in centigrade degrees, or 491.4 in Fahrenheit degrees. Ice may feel cold to the touch but it contains great quantities of heat. Water boiling under normal pressure is only 37 percent warmer than freezing water. Air at atmospheric pressure becomes a liquid when it is cooled to within 81 centigrade degrees of the absolute zero. The rare gas helium becomes a frozen solid at a temperature of 1 centigrade degree above absolute zero. The lowest temperature yet obtained is 0.16 degrees absolute, very close to the ultimate limit of coldness. What man cannot do is perhaps as interesting as what he can do. He cannot make anything colder than 273 degrees below the centigrade zero, and apparently he cannot make anything move faster than 186,285 miles per second. Why that speed is thought to be the ultimate record for swiftness is another story.

Speeds of the Molecules

For the moment let us content ourselves with the measured speeds of gas molecules. They are great enough to satisfy the demand for speed. We proved above that the pressure of a gas multiplied by its volume equals two-thirds of the total kinetic energy of the moving molecules. Knowing the numbers and

masses of molecules, and measuring the volume and the pressure under any temperatures we choose, we can calculate the molecular speeds.

As one might anticipate, the lightest molecules move the fastest. At zero degrees C. (273 absolute), hydrogen molecules, the lightest of all, average 6050 feet per second. This is more than a mile a second, 69.3 miles per minute, 4150 miles per hour. How many billions of billions of times that hydrogen molecule collides with its mates, and with the walls, in an hour, to build up that great mileage within, say, a bottle! An army rifle bullet moves less than half that fast when leaving the muzzle. Nitrogen molecules at the temperature mentioned above travel 1613 feet per second, oxygen 1510, carbon dioxide 1287. These of course are the average speeds; many molecules are moving faster, many more slowly. As the temperature rises, the general level of velocity rises according to the law based on kinetic energy. And if all those gases just mentioned were mixed in the same space, they would retain the same average velocities just given. The slower molecules would of course collide with the swifter ones, but their greater mass, or inertia, would prevent them from attaining the higher speeds. The speeds are related to the molecular masses in such a way that the average kinetic energy, which depends on both quantities, is the same for the different kinds of molecules at a given temperature. Thus the heavier gases are the last to leave a planet. The escape of atmospheres, together with other matters relating to molecular speeds, was discussed in Chapter 3.

The Molecules of Solids and Liquids

The evidence indicates that in liquids and solids, as well as in gases, the temperature depends on the speeds of the molecules. Here the molecules do not enjoy full freedom of motion, but

oscillate within narrow limits of range. That they do move, however, is suggested by the facts of diffusion. A drop of dye soon discolors a whole vat of water even without stirring, and two solids resting in contact will gradually interpenetrate each other if enough time is allowed. Solid gold is 70 percent heavier than solid lead; yet store lead on gold and in a few years you can find that molecules of the heavier gold have diffused upward into all parts of the mass of solid lead. How such motions can exist within an apparently poreless solid will become clear when we introduce the electrical evidence and find how important a role empty space plays in the composition of solid matter.

It should be understood that not all the kinetic energy of molecular motion, or heat, registers itself as temperature. Apparently only the motion of the molecule as a whole affects the thermometer. But compound molecules can also spin like dumbbells thrown through the air. Here we are getting into a difficult field in which we shall not attempt to go very far beneath the surface. Supercooling; the interlocking of molecules to form crystals; and numerous other phenomena, including electric, optical and x-ray effects, come to the aid of the scientist.

The apparent disappearance of heat energy during the processes of melting and evaporation is readily understood. When the molecules are as closely crowded as they are in liquids and gases, they attract one another. How great the forces of molecular cohesion are may be inferred from the result of an attempt to pull an iron stove poker apart. During melting or evaporation, work must be done to separate the molecules, just as in separating the plunger of a pile-driver from the earth. The kinetic energy of moving molecules, which is heat, now becomes, in part, potential energy. Thus in pulling the molecules of a solid apart, in loosening them up, so to speak, work is done, and potential energy is

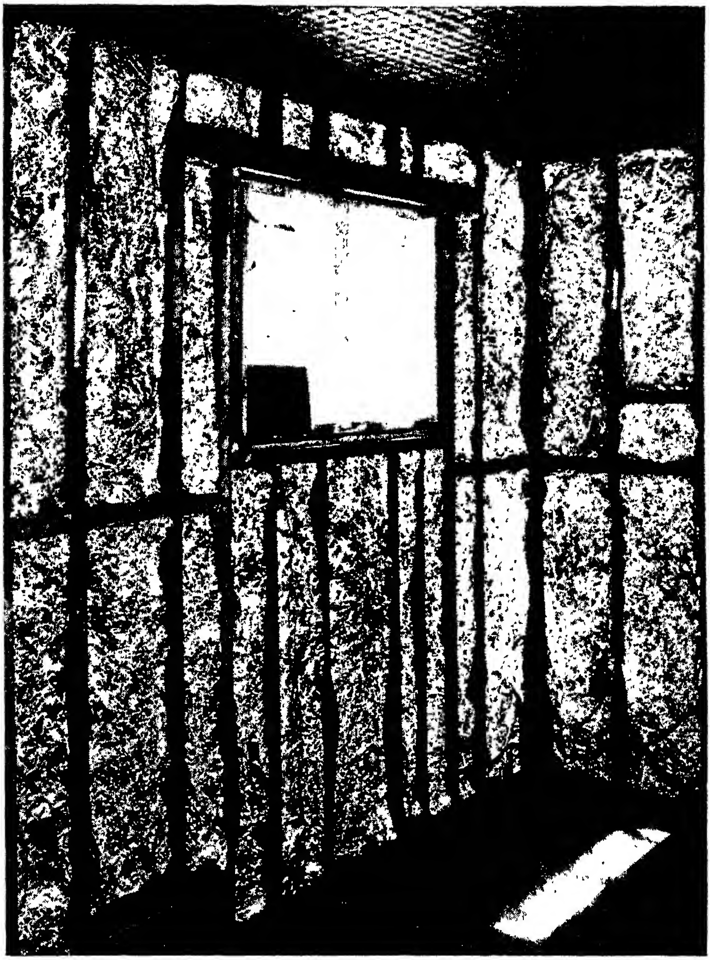


FIGURE 32. One means of reducing heat losses in winter, and heat gains in summer. The shining aluminum foil with which these walls are being stuffed during construction will continue to reflect radiant heat back in the direction from which it came. (Courtesy Aluminum Company of America.)

stored in the molecules. Just so, potential energy, the capacity for doing work, is stored in the raised plunger of the pile-driver. When the plunger falls the potential energy is converted into kinetic energy; when the molecules of the liquid fall back to closer grips with one another, their potential energy becomes kinetic, and we notice the evolution of heat associated with freezing. Similar phenomena occur during evaporation and condensation. Thus the quantity known as latent heat is understood without recourse to Black's ingenious hypothesis involving chemical combinations of the unreal substance caloric.

Cooling Processes

An understanding of many matters results from a knowledge of the nature of heat. The cooling of objects can be accomplished in a number of ways. The simplest, of course, is merely to allow the warm body to give up its heat to cooler surroundings by conduction, by convection currents, by radiation. But by this method the object cannot be cooled below the temperature of its surroundings.

Another method suggests itself. If a compressed gas expands against a resisting pressure, so that it must do work in expanding, it uses up some of its heat energy in doing the work and so cools itself.

Still a third cooling process is available: evaporation. The cooling of a wet finger in the breeze is familiar to all. The latent heat of vaporization is absorbed from the finger. Filling the cupped palm of the hand with the highly volatile liquid, ether, used in anaesthesia, and then directing a jet of air against the liquid to hasten evaporation, can easily result in freezing the palm of the hand. A jar of drinking water on the running board of a moving car remains cool if wrapped in cloth that is kept wet.

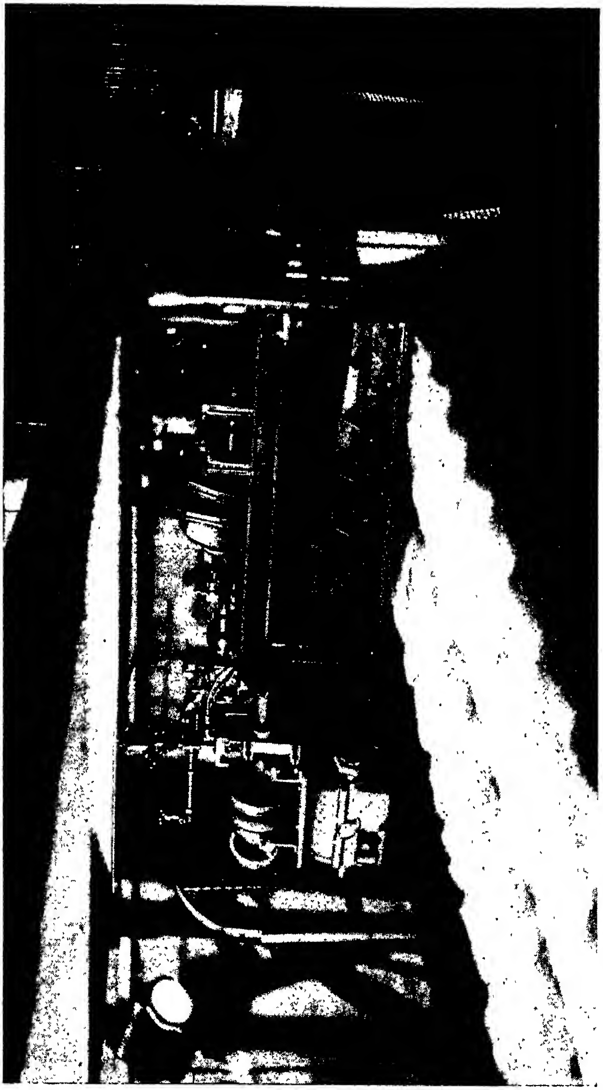


FIGURE 33. Another means of insulating against heat transfer. This soft mineral floss is coming from the melting tanks on an endless conveyor. The glass-like threads, each approximately one-tenth the thickness of a human hair, are poor conductors and also reduce convection by trapping the air. (Photograph by Ayres A. Stevens, Corning Glass Works.)

Refrigeration

Expansion and evaporation are both utilized in the usual refrigerating machine. A working substance is chosen which is a gas under ordinary conditions but condenses into a liquid under high pressure. Ammonia is commonly employed in ice factories, but household machines use a material that can be liquefied by lower pressures, such as sulphur dioxide. The working material is sealed in a system of tubes and a cylinder, and does not wear out.

The operation is easily understood. All that the electricity does, in the usual motor-driven refrigerator, is to operate a little pump, a piston working back and forth in a cylinder. There are automatic valves in the circulating system so that a one-way path for the sulphur dioxide or other refrigerant is provided. When the piston comes down, compressing the gas, the gas turns into a liquid. It therefore liberates heat, due both to the work of compression and to the latent heat of condensation. Thus the first operation in refrigeration produces heat. This heat is removed from the now liquid refrigerant by a stream of water from the faucet, or by a fan, or, in certain types, by a copper coil of many turns that exposes a large surface to the air.

Now we have a liquid at ordinary temperature, and under high pressure. Only that high pressure keeps the material liquid. The piston goes up, releasing the pressure. The liquid evaporates, and the vapor expands. Both are cooling processes. The refrigerant absorbs heat, first from itself, then from the coil that contains it, then from the food or other material in the vicinity of the cooling coil.

The process goes on in endless repetition, producing heat and absorbing heat, and the secret of success is simply to absorb heat

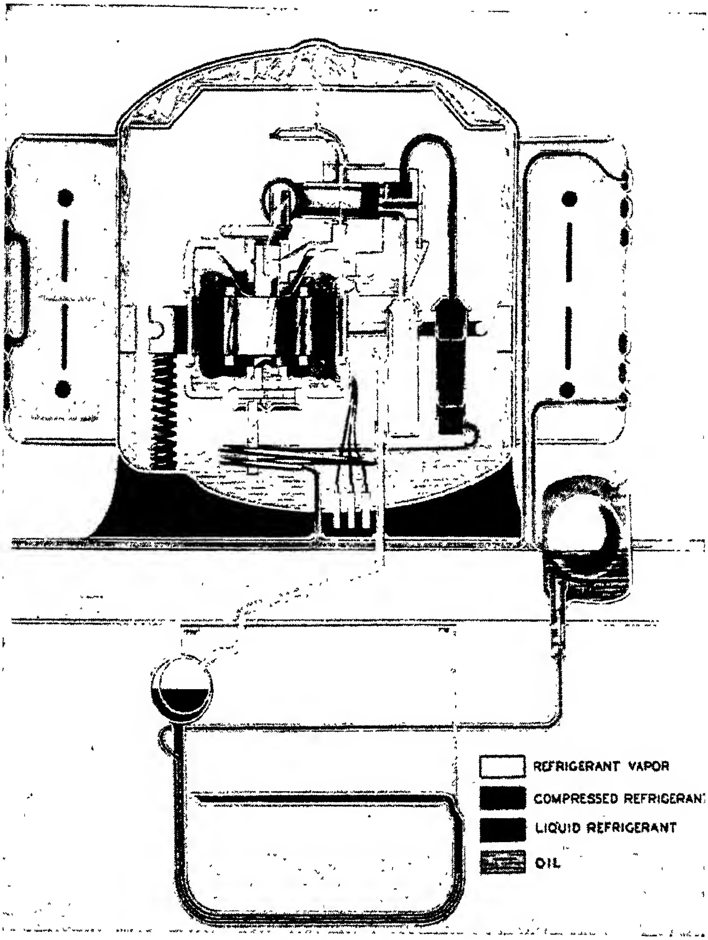


FIGURE 34. Evaporation is a cooling process. The sulphur dioxide used in this electric refrigerator is alternately compressed and vaporized. The refrigerant absorbs heat from the interior when vaporizing and expanding, and gives up heat to the surroundings when being compressed and liquefied. (Courtesy General Electric Company.)

in the region to be cooled, and give up heat in a region that you don't mind making warmer.

Evaporation, Dry Ice and Beachworms

Countless applications of cooling actions suggest themselves. "It's not the heat, it's the humidity." Overlooking the erroneous use of the word *heat* where temperature is meant, we see that evaporation explains the statement. The body depends on evaporation of perspiration for a cooling effect. If the air is already humid, the water vapor in the air retards evaporation, and one is deprived of part of the usual cooling action. If the humidity is 100 percent, which means that the air is saturated, containing all the water vapor it can hold at the existing temperature, the net evaporation from the body is zero. We say *net* evaporation, because although some perspiration evaporates, the cooling effect is counteracted by condensation of vapor on the skin from the air. Why is a fan's breeze cooling? All that the electric fan does is to take air from behind the blades and blow it on you, actually heating it slightly by friction in the process. But by this means fresh unsaturated air continually bathes the body and promotes evaporation, a cooling process. If the air is saturated, the breeze has no cooling effect unless the air itself is colder than the skin.

Dry ice is made by releasing the pressure on carbon dioxide which has been liquefied by enormous pressure. The sudden evaporation and expansion cool the gas so much that it freezes. A similar action is useful in medicine. For instance, the parasite popularly known as the beachworm sometimes enters the skin during the vacation season at sandy beaches, and slowly burrows along under the skin like a ground-mole under the grass of a lawn tennis court. Behind him the parasite leaves a winding path

of destruction which shows itself, about twenty-four hours later, as a painful red thread of inflammation. The physician gauges the location of the parasite by direction and distance from the end of the inflamed track, and freezes the skin in the suspected area by spraying it with compressed ethyl chloride. Released from the high pressure the ethyl chloride evaporates and expands, freezing not only itself but the surface skin and the beachworm. It takes just a moment, one goes off and forgets the dead parasite but perhaps gives a grateful thought to science.

The Ideal Heat Engine

The refrigerating machine may be looked on as a heat engine run backwards. What was once heat energy, operated the electric motor that pushed the piston that transferred heat from a body at a lower temperature to one at a higher temperature. In a sense, heat was pumped uphill — up a thermal hill — and work had to be done. Similarly, water can be pumped up a real hill if work is done. That elevated water can then do work while flowing downhill. It can turn a water wheel, for example, and generate electricity. Just so, heat can do work during the process of transfer from a source at a higher temperature to a heat-sink or condenser at a lower temperature. The comparison with water reveals an important difference between the two processes: only the energy of the water is used up in the water wheel, not the water itself; but in the heat engine the heat *is* energy and some of it disappears when the engine accomplishes work.

By heat engine we mean any device for utilizing heat to do work in a continuous cyclic process. If we were trying to become heat engineers, we should need diagrams of cylinders and pistons, turbines, valves, governors, drive-shafts. There would be im-

pressive tables of steam pressures at different temperatures, heats of combustion of coal, gasoline and oil. But we are looking for the basic principles which underlie man's application of heat to do work. Let us therefore give a moment's thought to the ideal, or perfect heat engine, one that exists only in the mind of the scientist and can never be constructed. It has a perfectly fitting piston, absolutely no friction, perfect insulation wherever insulation is desirable, and perfect conducting properties where conduction of heat is needed. By considering the ideal we quickly discover the goal towards which engineers can work, the best that can possibly be hoped for even if all mechanical or other imperfections are completely eliminated.

In the ideal engine some gas is shut up in a cylinder containing a movable piston. Heat is supplied to the cylinder; the gas expands, pushes the piston, does work, perhaps starts a flywheel to turning. In expanding, the gas would have cooled itself if no heat had been taken in; but the heat reservoir supplied heat. Now, in the second stage, the supply of heat is shut off and the hot gas expands still farther, at the expense of its own heat energy. Thus it does more work, but cools itself. We now face the problem of restoring the original conditions so that the action may continue over and over, in a cyclic fashion. In the third step, some of the energy stored in the flywheel is used to push the piston down, compressing the gas. The heat of compression is discharged into the surroundings, or perhaps to a specially cooled condenser. In the fourth and last operation, some more of the flywheel's energy is used to complete the down-stroke of the piston. The heat caused by this compression is not discharged but is left in the gas, which thus returns to its original high temperature, ready to begin another cycle.

Heat Does Not Flow "Uphill"

In our ideal engine the working substance is used over and over again, indefinitely. In actual steam engines the working substance is expelled at each cycle but, in large measure, reclaimed. In internal combustion engines — gasoline automobile motors and Diesel oil-burners — the working substance is transformed and thrown away through the exhaust. In actual engines there are many leakages and wastes of energy that do not occur in the ideal engine which we have pictured. Yet our ideal engine is amazingly inefficient! Since we assumed every man-caused source of inefficiency to be eliminated, the inefficiency must be the result of a fundamental principle of nature. What is it?

The principle sounds as simple as the law of conservation of energy — and its implications are scarcely less sweeping. Heat will not of itself flow from a colder to a hotter body. Thus, if heat is to be useful, it must exist in a hot body, so that it will flow of its own accord into the working substance. A large iceberg contains vastly more energy than does the boiler of a locomotive, but the iceberg's energy is unavailable. It will not run an engine, or keep the human body — a complicated heat engine — alive, unless we extract it with a refrigerating machine, and in pumping the heat out we should waste more useful energy than we gained from the iceberg.

For this reason, only part of the heat absorbed from the hot reservoir or boiler of our ideal engine does useful work. The remainder is discharged into the surroundings at a lower temperature. It is not lost, but its usefulness is lost. It becomes unavailable, just as the iceberg's heat is unavailable. The question is not conservation of energy. Of course conservation applies. For every 3.09 foot-pounds of work done, one calorie of heat disappears; and

if the amount of heat converted into useful work is added to that rejected to the condenser or wasted in leakage and friction, the result equals the amount of heat absorbed from the hot reservoir. But no matter how well-made a heat engine might be, it simply could not utilize all the heat energy of the coal, gasoline or other fuel unless the surroundings were at the absolute zero of temperature, 273 centigrade degrees below the freezing point of water.

Wastefulness of Heat Engines

An illustration will bring out the importance of this principle of nature. Carnot and others have proved that the efficiency of the ideal heat engine, the ultimate limit of perfection which engineers may seek but never attain, is equal to the result found by dividing the difference between the operating temperatures by the temperature of the hot source. Absolute temperatures must be used. Suppose a steam engine takes steam at 180 degrees centigrade from a high-pressure boiler, and rejects it into the open at ordinary atmospheric temperature. The temperature of rejection is then 100 degrees C. Adding 273, to translate to the absolute scale, we calculate the limiting efficiency to be the quantity (453–373) divided by 453, which is 0.176 or 17.6 percent! This means that the amount of heat wasted cannot possibly be less than 82.4 percent of the total. And any real engine operating between those two temperatures will be even more inefficient.

How can efficiency be increased? Either by using a hotter source, or by cooling the condenser where heat is rejected. Keeping the boiler temperature the same as before, but icing the condenser, would raise the limiting efficiency to 39.7 percent. In this case more than half of the energy would be wasted even if the construction of the engine were perfect; actually, the waste would

be much greater. Even if we both cooled the condenser with ice and ran the boiler at 356.9 degrees C. — the temperature at which mercury normally boils — the limiting efficiency would be only 56.7 percent, and actually more than half the heat energy would be wasted. At this last temperature the boiler pressure is 2606 pounds per square inch, 177 atmospheres. The temperature cannot be greatly raised without strengthening the boiler and the working parts correspondingly. Of course man knows how to do this. For a different purpose, Professor Bridgman of Harvard has used up to half a million pounds per square inch — a pressure some forty times that on the deepest ocean bed and more than enough to squeeze water, which until recently was considered incompressible, into about three-fourths of the space that it normally occupies. But practical considerations preclude the use of enormous pressures in heat engines. Hence the tentative experiments in which mercury vapor was substituted for steam, to secure high temperatures and relatively high efficiencies without excessive pressures. But hot mercury vapor is objectionable for a number of reasons.

Is the Universe Running Down?

We have made our point, and must pass on. Our brief lingering over the low efficiency of even an ideal heat engine has added one new concept to our gradually evolving picture of energy. Energy, though indestructible, may be degraded. Its availability may be reduced, even destroyed. Wherever one turns he finds heat flowing, and always from hotter to colder. Down the temperature hill it flows, incessantly down, like water — and we cannot get it back to the top of the hill without causing still more to flow downhill. Unless some countervailing action is at work somewhere in

the universe, a process entirely within the realm of speculation at present, the universe is running down, down the temperature hill. The bird is warm, it is now sitting in the top of a tree, singing a song. Its bodily heat exists above the temperature of its surroundings, and is therefore useful. The bird has the potential energy of high position, and that energy, too, is available, for with it the bird can descend upon a worm. The bullet of a marksman embeds itself. Now where is all that energy? The bodily warmth, the potential energy, the kinetic energy of the whizzing bullet? A little spot on the ground is slightly warmer than it was before. But not for long. Spread out at the dead level of the surroundings is now an extra bit of energy that was to be available but once.

The sun's surface layer contains heat energy at six thousand centigrade degrees above absolute zero. With a little of that energy it lifts some water. Rain falls, a cataract roars, a water wheel turns a generator. Eventually you press a button, and a lamp gives off a little light and heat. Now where is the energy? Your finger on the switch has done its bit to help the universe run down.

The substances with which we stoke our bodies can produce so much heat. Locked in the molecules, the energy is available. It can provide heat at the high temperature of a furnace or the modest 98.6 degrees Fahrenheit of an unfevered person. Choose either heat-death for that energy that you like, and the final result will be the same. Soon it is spread out at the dead level of the surroundings, its availability gone. Heat from the cold earth will not flow into one's body to run the human engine. Behind us wherever we walk, we leave an invisible trail of energy. A dog of an imagined breed — a thermometric bloodhound, if you like — could find the trail while it was fresh. Turn your eyes wherever you will, and every action that you see is helping this down-

ward trend of energy. The fall of the bird, the sound of the waterfall, the wind rustling the leaves, the foot on the road, the hand on the knob, the tides rubbing against the earth, the meteor writing its bright line just once in the sky, the star blazing in space — down the temperature hill, always down. An optimist, surveying this depressing prospect, may listen, if he likes, for news of some hitherto undiscovered creative process capable of staying the approach of an age when there will be no temperature differences anywhere. But apparently, one day the tale of the universe will have been told.

Chapter 9

ELECTRICITY AND MATTER

FROM our sublime but melancholy vision of a universe running down like a clock, we now turn to—electroplating! Science is full of strange twists and turns. Both historically and logically, we seek our first link between electricity and the nature of matter in a commonplace action which is applied daily in thousands of shops to improve the appearance and lasting properties of metallic objects. Michael Faraday, discoverer of electromagnetic induction, father of all the dynamo generators in the world, protégé of Sir Humphry Davy and youthful companion of the latter on that triumphal tour of war-torn Europe in the days of Napoleon's last stand—Faraday discovered the laws of electrolysis in 1833.

Intellectual Rise of Electricity

But let us not plunge into the midst of electrical developments without a brief reconnaissance. Parallel with the unfolding of the fundamental ideas which we have thus far considered in dealing with the relation of energy to matter, a fourth great movement was taking place: the intellectual rise of electricity. We say *intellectual* rise; for electricity assumed scientific importance well in advance of the practical applications which have revolutionalized civilization. Except for the land telegraph, which was invented in 1832 by the American Samuel Morse, successfully applied by others on a small scale in Germany in 1833, and first publicly demonstrated in America by Morse in 1837, virtually all the more important applications of electricity have come since the middle of

the nineteenth century. The first under-water cable was laid under the English Channel in 1850. A transatlantic cable, fruit of Lord Kelvin's ideas, first joined the continents in 1858. The original Gramme dynamo, one of the earliest electric generators to attain any commercial importance, appeared in France in 1873. Alexander Bell produced the first working telephone in 1876. Thomas Edison, passing electricity through a carbonized bamboo stem in a vacuum, gave the world the incandescent lamp in 1879.

Faraday's discovery of the laws of electrolytic action showed for the first time that electricity is intimately and quantitatively associated with the atoms of matter. Here was an advance of the greatest importance in the evolution of the broad fundamental principles which have determined our ideas of the underlying nature of physical reality. The year of discovery, 1833, occurs in the midst of the period when the great concepts of conservation of energy, the atomic nature of matter, and the kinetic nature of heat energy, were being established. Rumford bored the cannon in 1798, Davy rubbed the ice in 1799, Joule first publicly stated the principle of conservation of energy in 1843. Dalton published his atomic theory in 1808. Joule gave his first lecture on the kinetic theory of heat in 1848. In that same half-century, many important developments were taking place in electricity. Modern electricity was then born; but naturally the science of electricity, young though it is, did not spring suddenly into being without a history. How had this great branch of knowledge been faring while the thinkers from Galileo to Joule were laying the solid foundations of modern views of force, matter, and energy?

Early History of Electricity

It is a curious fact that although one observation of artificially produced electrification is attributed to Thales, the man with whom we began the first of the two thousand-year periods that antedated Leonardo da Vinci, the important discoveries are almost without exception of recent date. The first scientific treatise on electricity comprises a single chapter of Dr. Gilbert's book on magnetism, published in 1600. In this chapter, Queen Elizabeth's court physician stated that electrified amber attracts smoke particles, and described the first electroscope, a device comparable in accuracy to Galileo's crude thermometer. The word *electricity* was coined in 1646 by Sir Thomas Browne, a great physician who, like his famous contemporary Dr. William Harvey, discoverer of the circulation of the blood, was obliged by public opinion and royal pressure to assist in the examination of persons accused of witchcraft. In this period Otto von Guericke, whose experiment of eight horses pulling against the force due to atmospheric pressure has already been noted, was generating frictional electricity on a relatively large scale by holding his hands firmly pressed against a rotating sulphur globe. A little later, in 1729, Stephen Gray reported the then astounding fact that electricity could be conducted 700 to 800 feet from a frictional generator by means of wires or moistened strings.

Amusements of the Wizard of Wittenberg

At this time, long after Newton had published his *Principia,* electricity was regarded principally as a means of amusement. Professor G. M. Bose's adeptness in performing mystifying pranks with electricity gained him popular fame as the Wizard of Witten-

berg. As early as 1730, in the town where Protestantism had been born two centuries earlier, he set up a huge glass globe that was rotated rapidly by servants against leather friction pads, and with the electricity thus generated knocked over at one crash twenty soldiers of Frederick I, father of Frederick the Great. Bose invited guests to a banquet table and filled them with horror as they saw electric discharges burst forth from the viands. He introduced his guests to a popular actress, whom he had secretly insulated and connected to a friction machine concealed in an adjoining room, and, so the story goes, enjoyed the outcries that resulted when several young blades accepted his challenge to show their admiration for the lady in a manner that has not yet gone out of date. Despite his preoccupation with practical jokes, Bose found time for a heroic sentiment, saying he hoped to die of an electric shock, to furnish material for a report to the French Academy of Sciences; and in 1744 he improved the friction generator by adding a pointed inductive collector which changed the machine into very nearly the form that many experimenters used as late as 1900 to operate early x-ray tubes.

Serious Progress in Electricity

Charles Dufay, French physicist and chemist, was the first to distinguish between two kinds of electricity. In 1735 he defined vitreous and resinous electricity. Vitreous is the sort produced on glass by rubbing it with silk, and resinous electricity is the kind obtained on sealing wax rubbed with flannel. He added the important discovery that like kinds of electricity repel each other. Hitherto, only attraction had been observed, because the charges tested had, for lack of insulation, usually been unlike. Dufay proposed a theory of two imponderable fluids to account for elec-

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trical phenomena; but almost immediately, in 1747, Benjamin Franklin suggested the names positive and negative in place of vitreous and resinous, and thus substituted a one-fluid theory according to which negative electricity was merely the absence of positive electricity, much as cold is the result of loss of heat. Two years later, in 1749, Franklin drew lightning down his kite string, proving in this historic experiment that nature's lightning is kin to man-made electric sparks.

Galvani, Volta, Davy

In 1780 Luigi Galvani produced continuous currents for the first time. He produced them in frogs' legs, at first accidentally, then purposely by a means now recognized as contact electricity. A fellow Italian, Alessandro Volta — whose name is immortalized in the practical unit, the *volt* — immediately began an epoch-making series of experiments in generating electricity by the contact of two dissimilar substances. March 20, 1800, is an important date in the history of electricity. On that day Volta wrote to the president of the Royal Society of London a letter describing his voltaic pile, the first practical source of continuous electric currents. The prosaic flashlight cells and storage batteries of today are the modern improvements on Volta's piles.

Now events occurred with great rapidity. Within six weeks William Nicholson and Sir Anthony Carlisle had made a voltaic pile and *decomposed water into oxygen and hydrogen by means of the electric current.* Four months later, a solution of copper sulphate (blue vitriol) was decomposed into its constituents in Germany, metallic copper appearing on the negative terminal under the influence of the electric current. In 1807 Sir Humphry Davy used the same means to discover sodium and potassium.

These were liberated by passing electricity through the hydroxide compounds of the two substances. The shining metals, never before seen by man, appeared as if by magic under the action of the electric current. The law of this new kind of action (electrolysis), and hence its bearing on the nature of matter and electricity, was not to appear until 1833; but in the meantime the science of electricity was set on its feet by a series of discoveries which made the quarter-century one of the richest in the history of thought.

Foundations of Modern Electricity

Hans Christian Oersted, a Dane, discovered in 1820 that a current-carrying wire exerts a magnetic force on an iron magnet at a distance. Later in the same year a famous French scientist, André Marie Ampère, whose name has been given to the familiar unit of electric current, discovered that two current-carrying wires alone, without any iron in the vicinity, will themselves exert forces on each other at a distance. The force may be repulsion or attraction, according to the directions of the currents in the two coils or wires, and depends on the strengths of the electric currents. In the discoveries of Oersted and Ampère one sees the electric motor in embryo.

In 1822, Johann T. Seebeck, of Berlin, advanced contact electricity from the point of Volta's work by discovering that if a continuous metallic circuit of two *different* metals were made, and one junction kept warmer than the other, a continuous current would flow, no special source of electromotive force, or voltage, being needed. This effect finds wide application in modern electrical thermometry. One can read the temperature of an oven as far as he cares to run the wires; or, by using fine wires and

a sensitive current-measuring device, the temperatures of stars many light-years distant can be measured.

Four years later Georg Simon Ohm, of Germany, discovered the famous relation now know as Ohm's law, the rock-bottom foundation of all practical work in predicting the flow of current in a network of wires; and in 1831 Michael Faraday, the one-time bookbinder's apprentice to whom Sir Humphry Davy referred in later years as his own greatest discovery — Faraday discovered the principle of electromagnetic induction. By applying this principle man could now, for the first time in history, hope to achieve a powerful and satisfactory generator of electricity. The foundation of the electric age was laid. Two years later, Faraday announced the laws of electrolysis.

A Moment's Recapitulation

It is to one of Faraday's laws of electrolysis that we now turn for our first clue to the nature of electric energy. The impressive list of discoveries in the great field of electricity, which we have summarized so briefly in the preceding paragraphs, will of course receive further attention farther on in our study. Electricity plays fully as important a role in our attempts to understand the underlying nature of physical reality as it does in man's quest for power over nature in the practical affairs of modern life. What we are seeking in this unit is an insight into the nature of matter and energy, especially the relation between matter and energy. Starting, at the beginning of Chapter 7, with clear ideas of work, energy, and the broad principle of conservation of energy, we have witnessed the founding of the atomic theory of matter and of the kinetic theory of heat energy. We have drawn a distinction between atoms and molecules. We now know what heat is. We

know part of the truth concerning the structure of matter. We have examined, in passing, a number of practical applications of heat and chemical actions, and have noted a few great names and dates in order to place ideas properly in the history of thought. We have arrived at the depressing concept of a universe that tends to run down.

But all the while we have been trying not to lose sight of our principal objective in this unit, which is not only to learn what matter and energy really are, but to see why we are forced to accept the views which we do accept. Discovery after discovery has carried us below the level of superficial appearances, down towards the unseen heart of physical reality. We have not yet dealt with electric energy, or with light, sound, and chemical energy — but we are ready now, with the aid of one of Faraday's laws of electrochemical action, to make an important and far-reaching advance.

Electricity Is Atomic

Faraday's discoveries in electrolysis established the atomic nature of electricity by evidence which bears a striking resemblance to the facts tabulated in our seven-item illustration showing the quantities of several elements which entered into certain representative chemical combinations. There, after arbitrarily choosing 16 units by weight of oxygen as a starting basis, we saw that certain definite amounts of other chemical elements were, as we said, consistent with that amount of oxygen, so far as chemical combinations were concerned. Either 1.008 units of hydrogen, or exactly twice that amount, namely 2.016 units, were found in combination with 16 units of oxygen; and in building up a system of compounds based on a 16-unit amount of oxygen we discovered either certain definite quantities recurring, or else small multiples or

simple fractions of those quantities, such as twice, or one-half. What Faraday found was that, when chemical compounds were decomposed or dissociated by means of electricity, those same quantities of the elements were always associated with either a certain unvarying amount of electricity or a small exact multiple of that quantity.

A Unit of Electric Quantity. The meaning of this will appear in a trice once we consider a numerical illustration or two. First, however, we need a unit by which to express how much electricity we are dealing with. The familiar *ampere,* named after the great French physicist, is a unit of electric *current,* or rate of flow. A 100-watt lamp, operating at the usual household voltage of 110 volts, draws a current slightly less than one ampere. The total amount of electricity that flows through the lamp depends both on the current, or rate of flow, and on the length of time it flows. As a unit of quantity of electricity, let us use the amount of electricity that flows through a wire in one second when the current is one ampere. This is the *coulomb,* a unit named for another French physicist. A coulomb, like a calorie of heat, cannot be visualized, but the usefulness of the unit is not thereby impaired. All we need pause for now is to note that quantities of electricity are readily and exactly measurable. For reasons of convenience, a larger unit, namely 96,500 coulombs, is often used.

Amounts of Matter and Electricity Compared. Suppose, now, that we undertake a project of silver-plating. In a solution of a suitable compound of silver we suspend the article to be plated and also a plate of solid silver, opposite each other. The silver is connected to the positive terminal of a battery, the article to be plated to the negative terminal. As the plating proceeds, we find that the more electricity we pass through the solution, the heavier the deposit of silver becomes. An exact proportionality exists,

which inevitably suggests not only that the silver particles are *carrying* the electricity, but that every elementary particle of silver is carrying the same amount of electricity. If we allow the current to flow until 96,500 coulombs of electricity has passed through the solution, we discover that the silver plate has grown lighter by 107.88 grams, and the article being plated has grown heavier by 107.88 grams. The quantity of silver chosen in this illustration, 107.88 grams, is the amount that fits in the system of atomic weights based on 16 grams of oxygen. This explains why we use 96,500 coulombs of electricity as our unit in this work.

Trying other materials, we find some striking results. *That same quantity of electricity,* 96,500 coulombs, if passed through a dilute solution of hydrochloric acid, liberates precisely the amounts of hydrogen and chlorine that fit in the system based on 16 units of oxygen. At the negative terminal there appears 1.008 grams of hydrogen gas; at the positive, 35.457 grams of chlorine. Or pass electricity through water. That same 96,500 coulombs of electricity liberates 1.008 grams of hydrogen and 8 grams (half of 16) of oxygen. To liberate 16 grams of oxygen requires exactly *twice* our chosen amount of electricity. In copper-plating, we pass *twice* 96,500 coulombs of electricity through a solution of copper sulphate to deposit the amount of copper that fits in the system of atomic weights based on 16 grams of oxygen.

Evidence of this striking relationship between matter and electricity could be heaped up almost indefinitely, but already the conclusion must seem inescapable to the reader. Since we have already proved that *matter* is atomic, we must conclude from this extraordinary quantitative agreement between atomic weights and quantities of electricity that electricity itself is atomic in nature. The molecules composing the solutions used in these electrolytic experiments are evidently broken up into electrified particles —

charged parts of molecules called *ions* — and these ions must each carry either a certain elementary unit of electricity or a small whole multiple — 1, 2, 3, etc. — of that elementary unit. In other words, electricity is not a continuous imponderable fluid, as the earlier views presupposed, but, like matter, is discrete, composed of small elementary particles.

Is Matter Electric at Bottom?

Thus electricity seems to be, in a sense, simpler than matter. In dealing with the 92 elements we find 92 kinds of atoms and 92 different atomic weights (besides a few special modifications known as isotopes); but in electricity, no matter what atoms we work with, we discover only one elementary amount of electricity, or small whole multiples of that one amount. Here, so far as these pages go, is our first inkling that electricity may be more elementary or fundamental than matter itself; whence it might seem easy to suspect that matter, this tangible stuff that we can squeeze and kick, may be essentially electric at bottom.

But let us not press any results farther than the evidence warrants. We have found a striking relation, an exact relationship, between matter and electricity; we have good reason to believe that electricity is atomic in nature; and now — let us see what we shall see. From the point which we have now reached the science of electricity progressed by leaps and bounds, and we, too, emulating the history of one of man's mightiest servants, can do likewise. Our foundation, though intentionally as nearly non-technical as the hunt for clear ideas permits, seems sound and sure. We have seen at least one sure reason for every major conclusion that we have been asked to accept in our search for the underlying essence of physical reality. Familiarity with the sort of thinking that is

needed to satisfy an exact science may not breed contempt, despite the popular aphorism — but at least it ought to make for easier going in the future.

Cathode Rays

Electricity traversing liquids taught us something. Electricity passing through gases teaches us more. A few years ago one needed to go into a laboratory to witness the beautiful effects of electricity coursing through rarefied gas in a partially evacuated glass tube. Now one finds electric tubes illuminating advertising signs throughout the land. The gas tubes supply light efficiently, not wastefully. The light is not a relatively feeble by-product of heat, as in incandescent lamps. Neon, argon, mercury vapor are widely used, each giving its characteristic and unmistakable bright lines when the light is analyzed with a spectroscope. In so short a time have the greater cities changed the character of their lighting, contributing millions of candlepower of neon light to the night sky, that a hypothetical race of lunar astronomers (if we care to imagine beings so impossibly clever as to have circumvented the appalling conditions on the moon) might well by this time have confirmed their earlier suspicions that intelligent life exists on the earth. Our greatest cities, hitherto doubtless suspected because of their appearance as smoky patches by day, massed hazes of light by night, would probably have revealed their identity to the imagined lunar astronomers by the sudden change of the spectral quality of the night illumination — a change occurring too suddenly to be attributed to natural physical evolution.

Leaving this interesting question — Is there intelligent life on the earth? — to any readers who may care to combine the one

fanciful idea of lunar beings with a good deal of sound physics and astronomy, we point out that for about three-quarters of a century it has been known that the ease with which electricity traverses a gas depends on the pressure. At ordinary atmospheric pressure, very high voltages ranging upwards from about 10,000 volts per inch (some 23,000 volts for the *first* inch between needle points) are required. The value depends on the humidity and the shapes of the metal electrodes between which the spark passes. As the pressure is reduced with a vacuum pump, the discharge occurs with greater and greater ease, until at a certain low pressure the same voltage that would break down only a fraction of an inch of ordinary air will produce a beautifully luminous discharge through a tube many inches long. Further exhaustion below this optimum pressure increases the difficulty, until at the highest attainable vacuum, as in a modern high-voltage x-ray tube, several hundred thousand volts may safely be applied to cold metal electrodes no farther than an inch apart, without fear of breakdown.

Crookes Tubes. The tubes in which we are especially interested are called cathode ray tubes, or Crookes tubes. Once used merely to study the nature of electricity in laboratories, cathode ray tubes have come into industrial use. As we shall see when we study television in Chapter 14, electron guns (cathode ray tubes) may soon be as familiar to the American public as radio tubes are now. Sir William Crookes was a self-taught English scientist who, with little schooling as a boy, and never any connection with a college either as student or professor, made notable advances in science. He devised improved means of producing high vacua in 1873; invented the radiometer often seen whirling its vanes in the sunlight in opticians' windows in 1875; improved cathode ray tubes and began publishing important discoveries dealing with

the rays in 1878; invented the spinthariscope for detecting individual atoms shot from radium in 1903; and died in 1919, honored as one of the leading scientists of the day. Crookes tubes contain air at so low a pressure that they are nearly dark when operating; but the desired effects are detected by the light which certain *fluorescent* materials, interposed at suitable places, emit when struck by the invisible electricity that travels through the tube. What we want here is a collection of four noteworthy facts that are brought to light by means of four special Crookes tubes. The effects, which are beautiful, should be seen if possible; what follows may be considered to be the notes written down by an observer.

Four Conclusive Experiments

1. The Shadow of the Cross. Tube #1 contains a Maltese cross which can, at will, be interposed in the path of whatever it is that comes from the negative electrode (cathode) in the tube. Beyond this cross there is material, usually merely the glass itself, which fluoresces vividly under the impact of what we shall call the cathode rays. The observation is, that when the aluminum cross is out of the way, the whole end of the pear-shaped tube fluoresces, but when the cross is swung into the path of the rays it casts a sharp shadow. Therefore something must be coming from the cathode; that something is unable to penetrate even the thin aluminum of the cross; and *it travels in straight lines,* for otherwise no sharp shadow would be produced. This first observation is what gives us the right to speak of cathode rays.

2. The Hot Spot. In this tube the cathode rays are focused, by means of a cup-shaped metal cathode, upon a thin sheet of platinum foil. The platinum foil becomes white-hot at the spot

where the cathode rays are focused. Therefore the *cathode rays carry energy, because they produce heat when they strike.*

3. The Electron Mill. Here a movable set of vanes, like a miniature windmill, confronts the cathode. The vanes are coated with fluorescent materials, to become luminous under the cathode ray bombardment. The vanes spin rapidly. If the Crookes radiometer, often mentioned in our pages, be looked on as a molecular mill, since it spins under the impacts of molecules, our present device may well be called the electron mill. The fact that the cathode rays push the vanes shows that they have momentum and therefore possess the properties of mass, or inertia. *They are material.*

4. The Magnetic Action. We now use a long tube containing an internal slit which transmits only a narrow beam of the invisible cathode rays. They strike a long fluorescent screen at a glancing angle; this renders their path visible, as a straight line. The north-seeking pole of an iron magnet is brought up close to the tube, and the beam promptly curves, not toward or away from the magnet, but at right angles. The magnet is reversed, to bring the south-seeking pole close to the tube, and the beam curves in the opposite direction. The beam is deflected in the same direction as a current-carrying wire would move under a similar magnetic action. *Therefore the invisible cathode rays constitute an electric current in space.*

The Electron

By this time the reader is doubtless ready to accept that particles of electricity are traveling through space in the tube. J. J. Thomson clinched the matter by a special study of the deflection of the cathode rays under both magnetic and electric forces. By accu-

rate measurements of the curvatures of the rays under measured forces, he was able to find the precise value of two quantities. One was the velocity with which the rays traveled. This turned out to depend on the voltage applied, and ranged from about a thirtieth to a third of the speed of light. Remembering how fast light travels, 186,285 miles per second in empty space, we see that we are now dealing with particles of matter that travel enormously faster than the molecules which we considered earlier in our study. Presumably, then, these particles are vastly lighter than molecules. Thomson's method did not permit him to sort out the mass of one of the particles from its electric charge, but he measured the ratio of the charge to the mass, and the great American physicist, Robert A. Millikan, recent Nobel prize-winner in physics, soon measured the charge separately, so that now all three quantities — speed, mass, and charge — can be stated.

Millikan's Oil-drop Experiment. In his historic experiment, Millikan electrified minute drops of oil by ejecting them from an atomizer and then observed them while they hovered in the air between two flat metal plates, one charged positively, one negatively. Thus electric forces were superimposed on the gravitational force that tended to make the drops fall. Millikan found that some of the particles were attracted to the bottom plate, some repelled by it, showing that both positively and negatively charged droplets of oil were present in the mist from his atomizer. By regulating the electric voltages of the plates he found that he could keep any drop he wished, positive or negative, hovering at one level in space, its weight entirely and exactly counterbalanced by the electric attraction of the upper plate and the repulsion of the lower plate. Knowing the distances and the voltages, and measuring the masses of the droplets by an ingenious auxiliary method, he calculated precisely what the charge on any given droplet must

be in order that the known electric field of force should exactly counterbalance its weight.

The results of these tests furnished spectacular and utterly convincing proof of the conclusions regarding the atomic nature of electricity which we based on the indirect evidence of Faraday's work. No matter what the total charge of a droplet of oil was, or by what means the drop had been electrified, the charge was always an *exact small multiple* of one certain basic amount of electricity. In other words, any amount of electricity, however produced, is 1 times, or 2 times, or 3, 4, 5, 6, etc., times, one elementary amount of electricity. That amount is the *electron.* No one has ever found anywhere in nature, or produced by any means, a charge equal to 6½ times, or 17¼ times, or any other fractional number of times, this basic charge. In terms of electrons, fractional amounts of electricity seem to be non-existent. Evidently we have come to rock-bottom in electricity. We have found the elementary particle of which all negative electricity is composed. Note the restriction to negative. The same numerical value expresses the elementary atom of positive electricity, the *positron,* but we shall have more to say about positive electricity in a moment. The electron may be considered the atom of negative electricity. Benjamin Franklin suggested the name, negative, on the assumption that positive electricity was real, negative merely the absence of positive; but recent findings show that negative electricity is not only real, but plays the principal role in the flow of electric currents.

Mass and Charge of the Electron

The amounts of matter and electricity which compose an electron are well-nigh inconceivably small. In an earlier section we

attempted to give some idea of the smallness of atoms and molecules, and of the staggering numbers of them which are required to form enough matter to be readily noticeable. Here we shall content ourselves with the bald facts, leaving the reader to make his own comparisons if he wishes to image the truth. Even the lightest known atom, the hydrogen atom, is so heavy in comparison with the electron that 1847 electrons are needed to match the weight of one hydrogen atom. In other words, the mass of the electron is $\frac{1}{1847}$ of that of the hydrogen atom. No one has ever detected a particle of matter of smaller mass than the electron.

Small as the mass is, it is sufficient to give the electron an appreciable inertia. Tolman and Stewart showed this in a very ingenious way. Their method was the electric equivalent of an experiment that can easily be performed with a wheel whose rim is hollow and filled with water. When the wheel is started spinning, the water at first lags behind; and when the wheel is stopped, the water, due to its inertia, continues to circulate for a while within the hollow rim. In the Tolman-Stewart experiment, the free electrons in a coil of copper wire wrapped around the rim behaved like water in a hollow rim. When the wheel was stopped very suddenly after having been brought up to high speed, the free electrons in the copper rim kept on going and thus produced a momentary electric current which was measured with a sensitive meter. This result not only verified the earlier conclusions regarding the mass, or inertia, of electrons, but also showed that in metals many of the electrons are free, or readily movable. That is the reason why metals are good conductors. Another result of the inertia of electrons was found by the writer during some experiments on electrification by impact. Whenever a metal ball collided with an anvil of insulating material, such as ivory, glass or

ebonite, the ball became positively electrified. The free electrons in the metal ball, like the drops of water in a wet sponge thrown against a screen door, kept on going. The insulating anvil gained electrons, and became negatively charged. The loss of these electrons left the metal ball with an unbalanced positive charge when it rebounded. This inertia effect should not be confused with frictional (contact) electrification.

The amount of electricity associated with the electron is also very small. The coulomb of electricity, which we mentioned earlier as being the amount of electricity that flows in one second through a lamp which is drawing one ampere of current, is so large in comparison with the electron that 6.28 billion billion electrons are needed to equal it. If the combined populations of three billion worlds, each as heavily populated as the earth, could stream in one second through a monster turnstile, the attendance enumerator would have on his hands a counting job comparable to that of the scientist who counts the number of electrons which pass in one second through the tungsten filament of an ordinary 100-watt lamp. Using another unit often employed in science, we express the same result by saying that the charge of the electron is 4.770×10^{-10} electrostatic units.

Is the Electron Pure Electricity?

The fact that science has succeeded in detecting amounts of matter and electricity as small as the electron, and accurately measured them as well, is noteworthy — but a point of still greater interest for the general reader can be brought out very quickly. The amount of electricity associated with the electron, small though it is, is enormous in comparison with the mass of the electron, the amount of matter it contains. This is shown strikingly if we

imagine one whole pound of pure electrons placed at a distance of two feet from another whole pound of electrons. The *gravitational force* of attraction between two one-pound pieces of ordinary matter at that distance is so small that exceedingly sensitive means must be employed even to detect the force; yet between these two one-pound aggregations of pure electrons which we have imagined the *electric force* of repulsion would be equal to the weight of 1.75×10^{28} tons! In Chapter 2 we found that the mass of the earth is 658×10^{19} tons. Thus the electric force of repulsion between the two one-pound concentrations of pure electrons would be more than two and a half million times the weight of the whole earth if we could weigh that much matter piecemeal at the earth's surface and then add up the results.

What conclusion shall we draw from this amazing result? If we consider the gravitational attraction — in other words, *weight* — as a fair indication of the amount of matter, which is what we do every day in the grocery store, and if we accept the electric attraction or repulsion as a fair measure of the relative importance of the amounts of electricity involved, then we are driven to conclude that the *mass* of the electron, in the usual mechanical sense, is virtually negligible in comparison with the *electricity* of the electron. In short, our result suggests that the electron may be pure electricity, and its materiality, so to speak, merely a consequence of the existence of the electricity. Let us distinguish sharply, however, between an inference, reasonable though it appears, and exact proof. We shall have more evidence on this point in a moment. Let us conclude here merely that we have hit on a second bit of evidence to support our earlier idea that electricity may be more fundamental, in terms of the ultimate physical reality, than matter itself. We drew that conclusion tentatively, remember, when we found that there is only one

elementary amount of electricity, but 92 different elementary atoms of matter.

Impact of Electrons Produces X-rays

Many of the most important developments of modern physics, theoretical and applied, have resulted from the success of experiments in which the electrons are removed from ordinary matter and caused to travel freely outside of wires in vacuous space. The electron is not to be thought of as shrouded in the mist of hypothetical uncertainties. The modern scientist deals as familiarly and as surely with electrons as he does with bricks and stones. In this unit we are primarily interested in a philosophical question — What is the underlying nature of physical reality? — but the practical applications of physical energy which we are reserving for a subsequent unit cannot always be sharply divorced from the philosophical problem. The discovery that a stream of high-speed electrons colliding with ordinary matter produces a penetrating light to which our eyes are not sensitive has led to large extensions of our knowledge of the nature of matter.

In describing four crucial experiments with Crookes cathode ray tubes we mentioned the greenish fluorescence of the glass under the bombardment of electrons. The great German physicist and benefactor of mankind, Wilhelm Konrad Roentgen, discovered in 1895 that an invisible light which he named x-rays was given off by the glass wherever it was struck by the cathode rays. The early x-ray tubes were, in fact, merely modifications of the Crookes cathode ray tubes. A greatly improved tube in which the supply of electrons is obtained in a different manner was invented in 1913 by an American physicist, Dr. W. D. Coolidge. The universal adoption of the Coolidge tube in medical, industrial and re-

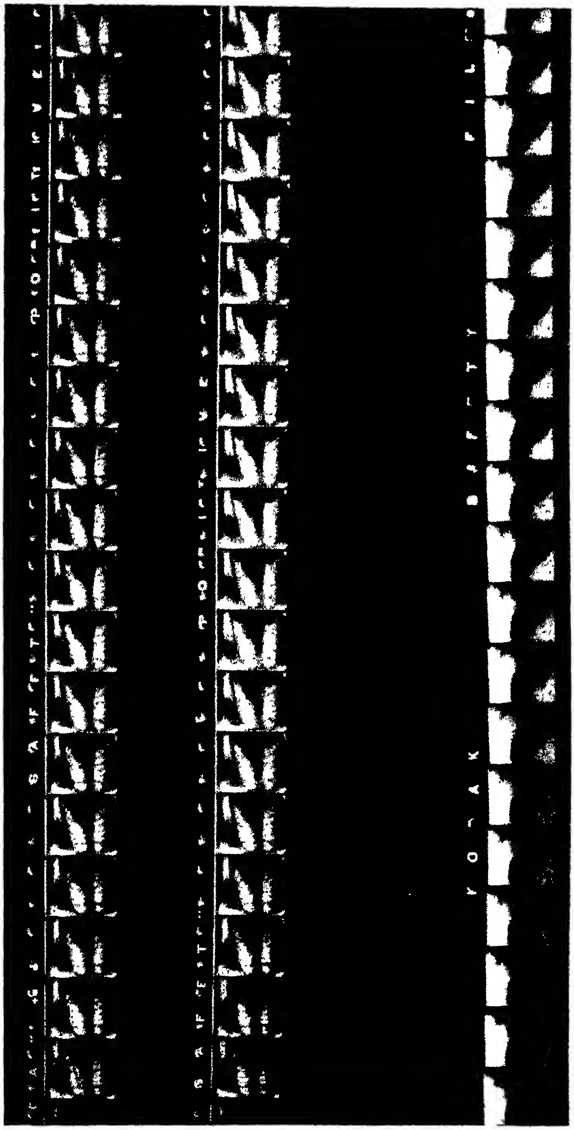


FIGURE 35. X-ray motion pictures of the human body. Chest and abdomen are shown in separate strips. Using a motion picture camera to photograph the visible image which the invisible x-rays produce on the fluorescent screen, Dr. William H. Stewart and Dr. H. Earl Illick have recently obtained films showing the human organs in motion. The films are projected in the usual manner. (Courtesy Dr. William H. Stewart.)

search laboratories throughout the civilized world in the inventor's own lifetime affords convincing evidence of the speed with which science progresses in this swift-moving age.

What we are primarily interested in here is the means by which the supply of electrons is obtained in the Coolidge tube. The tube contains two metal electrodes sealed into a large, highly evacuated glass bulb. One metal electrode consists of a coiled tungsten filament through which a low-voltage electric current is passed to heat it to whiteness. *The heat causes electrons to be evaporated out of the metal.* This important action — the Edison effect — was discovered by Thomas A. Edison and demonstrated by him at the Electrical Exposition in Philadelphia in 1884. Any metal heated to incandescence evaporates electrons. The electrons are always precisely the same, no matter what metal they come from. Here is further proof that the electron is one of the basic building blocks of the material universe. The electrons ooze out of the hot metal at low speeds, not nearly fast enough to produce x-rays by impact; but the other metal electrode in the x-ray tube, called the *target,* is maintained at a high positive potential or voltage, and thus attracts the negative electrons and causes them to collide with itself at speeds so great that x-rays are produced. Potentials ranging from a few thousand to a million or more volts have been used. The higher the voltage, the faster the electrons move, the harder they strike, and the more penetrating the x-rays which they cause the target to emit.

The x-rays themselves are a vibratory electromagnetic radiation which travels at the speed of light and is indeed similar in its basic nature to visible light, ultraviolet light, radio waves, and all other electromagnetic radiations. Fundamentally, x-rays differ from light and radio waves much as a high-pitched sound differs from the low note given off by a mechanism that is vibrating more

slowly. Except for a few materials (lead-glass, for example) x-rays penetrate matter much more readily than does visible light. Their photographic effect, their ability to cause certain substances to fluoresce visibly, and their therapeutic action are very useful to the physician. They ionize gases readily, breaking the molecules into electrically charged parts. Further, if one beam of x-rays of a suitable frequency strikes matter, that matter not only scatters the original x-rays but itself emits x-rays whose properties depend on the nature of the atoms which radiate the x-rays. This secondary emission of x-rays is called the characteristic radiation. The *characteristic* radiation depends on the *atomic number* (to be defined later) of the element on which the original beam of x-rays strikes. The fact that the atomic number is always a whole number furnishes additional evidence in support of the atomic view of the nature of matter. X-rays are one of man's most powerful tools for delving into the structure of matter. We have paused here merely to note that in the production of x-rays we find the energy of moving electrons being converted, in part, into the radiant energy of a vibratory disturbance which itself is not, in the ordinary sense, a stream of material corpuscles.

Electronic Action in Radio Tubes

One further illustration of electronic action should suffice to render us familiar with the idea that these almost incredibly small and numerous particles of electricity which we call electrons are real. In a typical radio tube of the simpler type one finds three metal electrodes — filament, grid and plate — sealed into an evacuated glass bulb. The *filament* is heated to redness so as to evaporate electrons, just as in the Coolidge x-ray tube. The *plate* is kept positively charged, to attract the electrons to itself across

the vacuum. This flow of electrons from filament to plate constitutes an electric current in empty space. Between the filament and the plate is a mesh of very fine wires, called the *grid*. The electrons traveling from filament to plate pass through the empty spaces between the fine wires of the grid.

Now suppose some feeble signal voltages received by means of the antenna are applied to the grid, so as to make the grid alternately positive and negative. When the grid is positive, it helps to attract the electrons towards the plate, and a greater current flows to the plate. When the grid is negative, however, it repels the electrons which are being evaporated from the hot filament, and thus opposes the plate's attractive effect. Here we find the secret of *amplification*. The purpose in view is to use the incoming signal voltages to make the plate current fluctuate. Further, we want the plate current to fluctuate more than it would if the signal voltages were applied directly across the filament and the plate. By applying the signal voltage across filament and grid, we take advantage of the grid's greater closeness to the filament. A small voltage applied to the grid produces as large a change in the plate current as would a much larger change of the plate's voltage. The grid acts as a very sensitive valve or gate to control the flow of electrons to the plate.

Thus, by applying feeble signal voltages to the grid, we produce relatively large fluctuations of the plate current — and once the plate current is fluctuating in response to the signal voltages, we can, by means of suitable accessories, produce sounds which will be reproductions of those that were made in the broadcasting studio. The energy of the sounds comes from our local supply, but that local supply of energy is *controlled* by the signal voltages which are applied to the sensitive grid.

The amplifying action can be repeated in a series of tubes, each

amplifying the output of the one that precedes it, so that a nearly infinitesimal amount of energy received by our antenna can control a very powerful supply of energy. Applications of this effect in radio, television, talking pictures, and industrial control will be considered in Chapter 14. It was by means of a series of such tubes that an electrical effect of light from the star Arcturus was amplified sufficiently to open the gates of the recent World's Fair in Chicago. The amplifying action can, if we choose, be carried so far that a single atom or electron can be detected individually, provided it is moving fast enough to ionize the air or other gas through which it travels. What we are stressing here is that the electron is so thoroughly real, and so well known, that billions of dollars have been confidently invested in projects whose success depended on the scientist's knowledge of the electron.

Chapter 10

RADIANT ENERGY AND ATOMIC STRUCTURE

A NEW phenomenon observed a year after Roentgen discovered x-rays opened an amazing new world to the curious eyes of physics and chemistry. In 1896 Henri Becquerel, working in Paris, discovered that certain compounds of uranium emitted, spontaneously and continually, certain types of penetrating radiation. Within two years Madame Marie Sklodowska Curie and her husband, Pierre Curie, had not only found that thorium compounds behaved similarly, but had isolated compounds of two new radioactive elements, polonium and radium. By this time numerous scientists, including, notably, Professor Ernest Rutherford of England, had plunged into the new field opened up by these epoch-making discoveries. Soon direct visual evidence of the existence of atoms was at hand to confirm the indirect though conclusive proofs afforded by the chemical data of Dalton and his successors. More than that, it became certain that the atoms of several elements were continually exploding, shooting out bits of themselves at high speeds. Not only did atoms exist, as Dalton proved, but, contrary to his ideas, *they had parts!* The universe of the sub-atomic revealed its existence to man. No longer could the material world be regarded as an aggregation of indivisible, hence perfectly simple, atoms.

Counting Atoms by Eye

Three types of radioactive emissions were discovered: the alpha, beta and gamma rays. The *alpha* rays were soon found to be

atoms of helium, each bearing exactly twice the charge of the electron, but positive instead of negative. The *beta* rays are identical with the electrons which we have already considered, and the *gamma* rays are x-rays of great penetrating ability. All three radiations are capable of affecting a photographic plate, of exciting certain substances to visible fluorescence, and of ionizing gases, which means breaking the molecules of the gas into electrified parts. It is the fluorescent effect that concerns us here. This is the action which causes the dials of self-luminous watches to be visible in the dark. Looking at the dial through a glass magnifying fifteen or twenty times, one sees a twinkling as of thousands of tiny stars, every twinkle the result of one atomic impact!

Suppose we shut ourselves up in a dark room with equipment consisting of a speck of radium compound, a good magnifying glass, and a piece of cardboard coated with pulverized crystals of zinc sulphide. Alpha rays from the radium atoms strike the zinc sulphide, each causing a flash of light which is visible through the magnifying glass. *We can count these electrified atoms of helium with the eye.* The experiment is simple and should be tried if the means are available. A few minutes spent in the dark room will render the eyes several thousand times as sensitive as they are in a well-lighted room. Further, if we care to collect both the helium atoms and the electricity which they carry, we can, by dint of patient counts and delicate measurements, find directly the number of atoms required to form a measurable amount of helium or to build up a certain quantity of positive electricity.

Perhaps no other simple experiment can give so satisfying a picture of the atomic nature of matter as does this experiment of counting atoms by the individual flashes of light which they produce when striking the fluorescent screen. One arrives at a con-

ception of the enormous numbers of atoms contained in a small amount of matter. Seven years ago from the time this is being written, a certain radium emanation chamber was prepared by putting a glass window in the top of an empty coffee can and mounting a small fluorescent screen under the window. A hole in the bottom of the can was then held for twenty minutes over a tiny speck — one-thousandth of a gram — of radium bromide. No radium was put in the can; merely a little of the radioactive gas, called radium emanation or *radon,* which is produced by the disintegration of the radium. The coffee can was then sealed up. It has never been opened since; yet the miniature flashes of light on the fluorescent screen are still too numerous to count.

What happened, in effect, was that twenty minutes' worth of the activity of the parent radium was sealed up in the can and started on an independent life of its own. The original speck of radium will go on suffering atomic explosions for many centuries, shooting away only one-half of itself in the first 1690 years. How small a fraction of its whole activity it gave to the coffee can during the twenty-minute exposure! Every twenty minutes during the seven years since the can was sealed up the original radium could have started off a new can on a similar history; and yet now, after all the years during which the atoms of the products of the original radium emanation have been exploding away in the can, day and night, several thousand per minute (not all of them near enough to the fluorescent screen to strike it), the flashes on the screen are still too numerous to be counted accurately with the eye.

If one will picture a great heap of nearly two hundred thousand similar cans, one for every twenty minutes in the seven years, atoms exploding in every one at least as frequently as in the one we actually observe, and then realize that even those thousands of

cans represent only a seven-year fraction of the activity of a speck of radium which will not be reduced to half-value until 1690 years have passed, he will begin to form an idea of the numbers of atoms which even a few grains of matter contain. Yet here he is detecting each individual atom by the flash which it produces. One must linger over these facts with his imagination if he would understand what marvels there are bound up in seemingly commonplace matter, and what feats the thought of man has accomplished in bringing them to light and proof.

Radioactive Transformations

The alpha particles which we have been counting in this experiment travel through air at speeds a few hundredths that of light; the beta rays (electrons) a few tenths. The gamma rays, which *are* a kind of light, travel at the same speed as light, 186,285 miles per second in empty space. The alpha rays penetrate at most several inches of the atmosphere or a sheet of tissue paper. The beta particles can get through several theater tickets or a thin sheet of aluminum. The gamma rays — nature's spontaneous x-rays — are vastly more penetrating: a beam from a few milligrams of radium can be detected after passing through a foot of solid iron.

Since alpha particles are ionized (charged) atoms of the gas helium, new substances are formed when these are expelled. Radium, for example, appears nearly half-way down in a long series that begins with the heavy metal uranium (atomic weight 238) and includes elements of decreasing atomic weight until that of lead (206) is reached. An atom of uranium explodes, expelling an alpha particle; the remainder is now a new atom, which eventually radiates and turns into something else; and so on. Three such series are known: the uranium-radium series,

the uranium-actinium, and another whose parent substance is thorium.

The laws governing the progressive disintegrations are so well known that, as we saw in Chapter 4, the age of the earth can be calculated by measuring the relative amounts of the parent substance and its products found sealed in a rock. Some of the radioactive elements are long-lived, some transitory. Half of an original quantity of uranium disintegrates in 4670 million years; half of some radium emanation in 3.85 days. Radium A, the residue left when atoms of radium emanation eject alpha particles, reaches half-value in three minutes; radium D, in 16.5 years. In our coffee-can spinthariscope, the radioactive matter left after the first few months was largely the long-lived radium D produced at the expense of the short-lived radium emanation by way of radium A, B and C; and the bright sparks on the fluorescent screen were due principally to alpha rays yielded by radium F (polonium), which disintegrates to half-value in 136 days but is continually replenished by radium D via radium E. Not all of the radioactive elements emit alpha rays. Radium E, for example, radiates only beta and gamma rays. The loss of a beta particle (electron) does not change the atomic weight appreciably.

Every second a certain fraction of the total number of atoms present explode. The value of the fraction is different for different radioactive substances; but for a given element it remains constant, *regardless of anything we may do,* until the disintegration is nearly complete. What happens when only a few atoms are left, too few to permit the fractional law to apply, we do not know. Half of an original number of radium atoms explode in the first 1690 years; half of the remaining half in the next 1690 years; half of the residue in the next 1690 years; and so on and on through the ages. This law is followed with mathematical

accuracy, second by second. For different elements merely change the number to the proper value, and substitute seconds, minutes or days for years, according to the element under consideration, and that same law holds rigorously. Yet what determines which particular atoms will explode in any given second? Why is one atom exploding at this instant, while a supposedly identical mate next to it waits a second or a century or a million years before taking the leap? Does some unknown agency draft the atoms for this duty of self-destruction? Do atoms volunteer, second by second, in exactly the right numbers to satisfy the law? Does cause-and-effect rule here? Recent successes in producing radioactivity in ordinary elements by artificial means suggest that this difficulty may possibly be resolved in favor of cause and effect, in the usual sense of the words, when we learn enough — but apparently we have come upon a question fraught with philosophical implications that may touch the foundation of morals. To turn the question aside by saying that probability rules is too glib, no more enlightening than to recite the insurance man's mortality tables to the coroner when he is trying to find out why Mr. So-and-So died last night.

At the end of the book we shall return briefly to this challenging enigma. Radioactivity is only one of a number of phenomena which bring physicists and philosophers alike face to face with the three-horned dilemma of complete causal determinism versus free will versus chance (whatever chance may be). This word is sometimes misused. If one sits blindfolded in a chair, tossing a short nail at random upon a floor covered with checkerboard linoleum, a mathematician, using the laws of chance, can foretell very nearly how many times out of every thousand throws the nail will come to rest across a line instead of lying completely within a square. This is a fair example of chance; but it *is* chance

only because we did not take the trouble to define the conditions and forces. The physicist knows that the resting place of the nail is determined jointly by the motion it has at the instant of leaving the hand, by gravitation, and by several other definable conditions. But to say that chance determines which thirteen of a million million atoms of radium (the actual rate) will explode in a given second, is to misuse the word. If the atoms *are* all identical, and if no forces act on the ones which explode that do not act on the others, what is operating is not chance, but either free will or a non-physical control of some sort. Physics has not accepted either of these alternatives in the world of atoms. Free will means the absence of causation — the possibility that a given situation may, if repeated, produce a different result, or that two situations which are identical in all respects may yield different results. A conceivable escape is to suppose that the atoms are not identical, but that each is a time-bomb, set to explode after so many seconds, minutes, years or centuries. This would necessitate a number of other seemingly incredible hypotheses which may occur to the reader. The possibility that an unknown radiation may detonate the atoms seems to be ruled out by the fact that the same fraction of the atoms explode every second regardless of time, place, melting, freezing, dissolving, shielding, chemical reactions, pulverizing, scattering to the winds or burying in a mine. Possibly the solution of the mystery will be discovered during the reader's lifetime. One of the most fundamental issues that can be imagined is at stake. To say *chance* is merely to dodge the question.

We merely suggest the problem here, in all its baldness; but no loosely thought conclusions should be accepted. The manufacturer planning to invest a million dollars on the strength of a law of physics or chemistry can count on the law to work every second of every day for as long as time may run. In practical

matters, the numbers of atoms or electrons dealt with are always so great that any uncertainty about the behavior of individual particles cannot affect the outcome. There is a remote resemblance, to be sure, to the situation in the studies which deal with humanity in the bulk, statistically; but whereas in the physical realm the individuals about which some uncertainty exists are the entirely negligible (for all practical purposes) atoms and electrons, in the social field the individuals whose behavior cannot be satisfactorily predicted are whole human beings, of whom none is negligible and some few can, as leaders, influence the course of events. In opposing single atoms and electrons, on the one hand, to whole human beings on the other, we seem to imply that exact laws of *aggregations* of individuals do exist in the social sphere, and in other respects also are sinking our probe into debatable ground. Physical science is justly proud of its success in pushing uncertainty back so close to the wall; but the wise reader will seek ideas in many fields before drawing hard-and-fast conclusions in matters outside of the exact sciences.

Radioactivity has brought another problem to light, the problem of sub-atomic energy. We saw in Chapter 7 that whenever whole atoms combine with other whole atoms to form chemical compounds, or whenever whole atoms are rearranged in any manner in chemical reactions, energy is always either absorbed or liberated, depending on the nature of the reaction. But in radioactivity individual atoms are coming apart. That energy is liberated in the process is proved by the light which we saw in the coffee-can spinthariscope. A gram of radium in equilibrium with its products liberates 120 calories of heat per hour, and will keep itself warm if insulated. A cubic foot of radium — a fantastic amount (at present) of this material which costs several hundred times as much as diamond gems — would keep a six-room house

warm winter after winter in mid-temperate latitudes, and after 1690 years would still be going half as vigorously as at the start. Consider how much coal would be burned in that time. Radium gives off in its lifetime 250,000 times as much energy as can be obtained by burning an equal amount of pure carbon. The energy locked up inside the atoms of matter dwarfs all other known sources of energy. In certain special experiments, atoms of ordinary matter have been taken apart artificially, but no practical means of tapping the enormous reservoirs of sub-atomic energy have yet been discovered.

Atoms Are Largely Empty Space

The discovery that atoms have parts led at once to the question, How are those parts arranged? Small as they are, atoms are mostly empty space. The alpha particles show this very clearly when their paths are photographed. Of course, no lens will form an image of an atom, but under certain conditions its *path* can easily be photographed. The alpha particle breaks up many molecules of air to form electrified ions, and on these ions water vapor tends to condense in tiny droplets. C. T. R. Wilson perfected this beautiful method of studying the paths of single atoms as they shoot through the air. The air is suddenly expanded (releasing a compressed atomizer bulb suffices) and the cooling produced by the expansion causes moisture to collect in miniature dewdrops on the ions formed by the speeding alpha particles. Thus the path of the particle stands out as a narrow track of glistening water particles.

An alpha particle crashes through atoms at such a speed that, *in proportion to mass,* it possesses approximately four hundred million times as much kinetic energy as a rifle bullet. The alpha

particle penetrates about 100,000 molecules or atoms in traversing two inches of air at ordinary pressure. One might think it would rebound this way and that as a result of the collisions, but on the contrary, the path is nearly straight until the end of the range

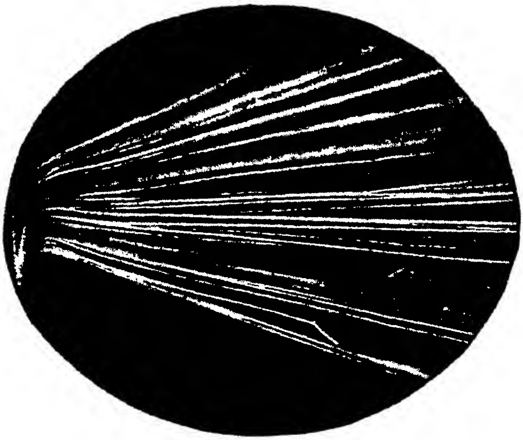


FIGURE 36. Tracks of alpha rays photographed by Wilson cloud chamber method. Most of the rays penetrate atoms without striking nuclei, but the forked track shows one that did. A proton was emitted, forming the upper branch; the remainder of the atom produced the lower branch. (Photograph by Professor W. D. Harkins, reproduced from Hausmann and Slack's *Physics.*)

has been reached. At the end there is sometimes a sharp deflection of the track, and always the stopping of the particle is very sudden and definite.

The *straightness* of the path is revealing. A meteor shooting through the earth's atmosphere encounters the most matter per second, and therefore the greatest resistance, when moving fastest; but if the meteor were fired as a projectile through the whole solar system it would encounter the *least* resistance when moving fastest, for then it would be opposed only by gravitational attractions and

their effect would be minimized by the shortness of time during which the speeding meteor remained in a given field of force. This illustration brings out one fundamental difference between the stopping of a projectile by actual encounters with matter, and the stopping due to resisting fields of force. The straightness of the path of the alpha particle as it plunges on through atom after atom, and its sudden stopping as soon as its speed has been reduced below a certain value, show that the resistance to its motion is not due to actual collisions with matter in the ordinary sense, but to the effect of attracting forces which are exerted on it as it penetrates the atoms. In other words, the flight of the alpha particle through an atom resembles the behavior of a meteor shot through the solar system, rather than that of a meteor shot through an atmosphere which is thickly filled with matter. But in using the meteor and the solar system for purposes of comparison, we should not gain the impression that gravitational attraction is what slows down and eventually stops the alpha particle as it plows its way through atoms. We have already noted the fact that when an atom is broken, the parts are found to be *electrified,* and a few pages back we saw that forces of electric attraction are vastly greater than gravitational forces for comparable quantities and distances. The alpha particle is slowed down by electric forces.

The results of these alpha ray experiments, together with a number of other findings which must be omitted here, show that the atom is largely empty space. Incredible as it may seem, the atom resembles the solar system in so far as the proportion of empty space to what, for lack of a better word, we may call actual matter, is concerned. Difficulties are piled on difficulties as one attempts to form a sound picture of what actually happens when one large body is brought to rest by collision with another. Since the atoms themselves are largely empty space, and since there is

additional space between whole atoms or molecules, is it conceivable that a man might at some instant find the empty spaces in his bodily structure arranged to fit the particles of a brick wall perfectly, so that he could project himself through it without leaving a hole? One might possibly gain this idea by reflecting that one swarm of heavenly bodies can pass through another without serious mishap if the bodies are suitably arranged, and widely enough spaced, at the time. But our brick wall experiment will never succeed. The probabilities are enormously against the precise registering of the empty spaces, and moreover, we saw at the beginning of this section how extraordinarily great the amount of kinetic energy is which enables an alpha particle to overcome the electric forces as it plows through atoms. Even in empty space, a man would need to fall steadily for three weeks under a force equal to his present weight in order to gain as high a speed as that of the swifter alpha particles — and if he ever moved that fast in air he would become a super-meteor outshining any that we see.

Light Is a Wave Motion

Besides establishing that atoms are composed of widely separated parts, radioactivity has illustrated for us the two fundamental forms of radiant energy: corpuscular, and wave motion. The alpha and beta rays are, as we have seen, streams of high-speed corpuscles of matter, and the gamma rays are waves. If a warship riding at anchor in a bay is to transfer energy to another ship at a distance, it can do so by either of two means. It can fire off its artillery and land projectiles on the decks or against the sides of the other, or it can agitate the water in its own vicinity and thus originate waves which will eventually set the distant

vessel to rocking. In the one case, matter is transferred, carrying energy with it; in the other, energy alone. What concerns us in this entire unit is the underlying nature of physical reality, which is to say the nature of matter and energy; and we have come far enough to realize that the two problems are intimately related. We have found that both matter and electricity are atomic in the sense that they are discontinuous, composed of great numbers of small interchangeable parts; and that atoms themselves are divisible into parts. In the field of energy we have seen that heat energy is the kinetic energy of motion of molecules; that the energy of an electric current is due to the motion of electrons; and that one form of radiant energy, illustrated by the alpha and beta rays, consists of small bits of electrified matter moving at high speeds. Like the maid crossing the brook in the painting, we are choosing our stepping stones carefully, lifting up our skirts to avoid entanglement with extraneous matter, and setting our feet squarely on one rock after another in our quest for a firm footing as we progress through this great ocean of truth.

In stating that gamma rays are a wave motion similar to light we have, however, taken the nature of light for granted. How do we know that light is a vibratory disturbance possessing the characteristics of wave motion? Suppose the reader looks at a bright cloud, or a distant arc lamp, through a slit made by holding two fingers very close together two or three inches away from the eye. On adjusting the width of the slit to the proper narrowness, one sees a beautiful pattern of fine black lines running parallel to the length of the slit. The slit is open, there are no obstructions in it — yet there in open space one sees a pattern of black, the *absence of light!* Patterns of still greater beauty can be observed by learning to use the eyelashes as a diffraction grating or screen through which to view a distant street lamp on a dark night.

With a little practice, one may become so interested in this beautiful experiment that there is danger of missing an engagement. These curious effects are due to an action called *interference* — and interference is the crucial test of wave motion. Many effects of interference can be observed. Soap bubbles are made out of milky-hued water; the beautiful reds and blues observed in a mass of soap suds are the result of interference. The iridescent sheen of a thin film of oil on a pond or wet street is caused by the same action. If one will hang up a screw, a wire, a small lead shot, and a piece of fine-mesh wire netting in the path of a narrow beam of light coming from a pinhole in an opaque window shade, he can see interference patterns of almost infinite variety and beauty. Merely look through a magnifying glass at the pinhole past the small obstruction. For example, wavy lines are observed in space around the screw, and there is a point of light at the center of the shadow of the solid opaque lead pellet. These effects, when analyzed, prove beyond a doubt that light consists of a wave motion.

Suppose we let the colors of a soap bubble stand for this whole family of effects. Why does the bubble appear colored when viewed by white light? White light, as everyone knows, is a mixture of many colors. This is shown by analyzing a narrow beam of white light with a prism spectroscope. The light is bent (refracted) when it enters the triangular piece of glass. It is bent again when it leaves the prism; and since every different color contained in the light is bent its own appropriate amount, the different colors are dispersed into a *spectrum*. If light from an electric lamp is analyzed, a *continuous* spectrum is obtained — violet, indigo, blue, green, yellow, orange, red. The red is deviated least, violet the most. But if the spectroscope is used to analyze the characteristic orange light produced by throwing

some common salt (sodium chloride) into a colorless gas flame, a *discontinuous* spectrum characteristic of sodium is obtained. This consists of two orange-yellow lines so close together that they appear as one unless the instrument is an excellent one. By holding a wad of asbestos, previously soaked in a solution of several chemicals, in the flame, the characteristic colors due to each chemical are obtained as a series of bright lines in the spectrum, each placed where the same color would be found if white light were being analyzed. Darkness, the absence of light, separates the lines. These bright lines — the fingerprints of the elements — show which elements are present in the original mixture. Electricity, also, causes chemical elements to emit their characteristic light. The spectrum of the light from an arc passing between two iron wires, for example, or the luminous glow of the ionized gas in a neon lighting tube, reveal hundreds of characteristic lines which identify the iron or the neon. These characteristic spectra should not be confused with the continuous heat spectra; the latter are determined, not by the chemical nature of the hot material, but by its temperature.

If to these few facts about light, especially the composite nature of white light, we add the principle of interference, the colors of soap bubbles can be understood. First, picture some ripples spreading outwards in concentric circles from a center of disturbance in a pool of water. At one instant, a certain particle of water is high, on a crest; a moment later it is in the trough. The wave motion causes the water to vibrate rhythmically up and down. Now suppose that two sets of ripples are crossing the region simultaneously, from two centers of disturbance. If the crests of two waves reach the particle simultaneously, they cooperate, lifting it higher by their joint action than either alone would have done; but if they come together out of step (out of

phase) they oppose each other's effects, and thus either wholly or partially neutralize each other. If the two sets of waves are exactly opposite in phase, one wave tending to raise the particle to a crest whenever the other tends to lower it to a trough, and if

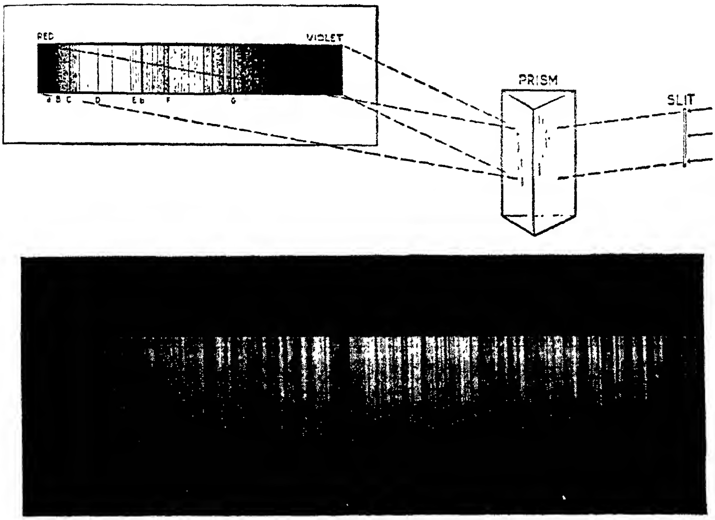


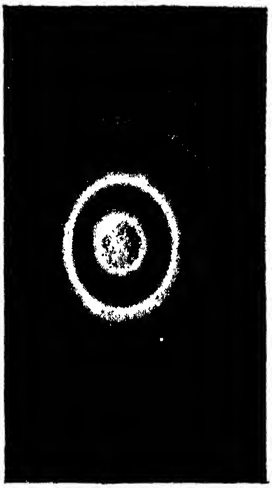
FIGURE 37. Effect of a prism, and a photograph showing part of the sun's spectrum. The dark Fraunhofer lines, caused by absorption in the sun's atmosphere, show which elements are present there. (From Robert H. Baker's *Introduction to Astronomy*.)

they are also of equal intensities, they will completely nullify each other's effects and leave the particle quiescent. In this special case, destructive interference is complete. If light is a wave motion, the result equivalent to the quiescence of this water particle would be darkness. Thus we see at least the possibility of finding dark lines in the open space between the fingers in our simple finger-slit experiment. The fact that, if certain conditions are satisfied, two beams of light, or rather different parts of one beam, can produce darkness when added together, proves that

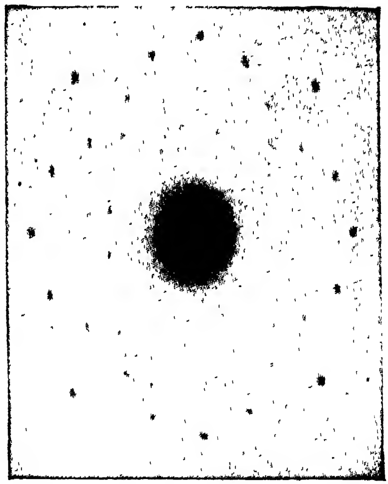
light is a vibratory disturbance possessing the characteristics of wave motion.

But let us stick to our soap bubble. The wall of the bubble is a thin, and nearly transparent, film of water. We see the bubble by reflected light. Some of the light that it sends to our eyes has been reflected by the outer surface of the thin wall; some by the inner surface. Thus the original beam of light that illuminates the soap bubble is broken up into two, and the beam reflected by the inner surface of the thin wall must travel farther than that reflected by the outer surface. One beam travels an extra distance equal to twice the thickness of the wall — going and returning — and if that extra distance is the right length, the two beams will find themselves out of phase when reunited at the eye, and so will interfere. If two apparently endless columns of soldiers are parading shoulder to shoulder down the main avenue, and at a certain corner one column keeps on straight ahead while the other turns to the right, marches around the block, and rejoins the other column at the next corner, what condition must be satisfied if the two columns are to find themselves shoulder to shoulder again, without any hedging, at the instant of reunion? The extra distance traversed by the column that went around the block must be equal to a whole number of paces. For light, substitute wave lengths for paces, and the conditions for a shoulder-to-shoulder reunion (in phase) can be obtained; also the halfway-in-between state of affairs which will bring the beams together exactly opposite in phase. Suppose the extra distance traversed by the beam reflected from the inner surface of the soap film is such as to cause the *blue* portions of the two beams to be out of phase. Then blue will be either wholly or partially destroyed by interference, and the red of the white light will predominate. The bubble, although illuminated by white light, will appear red when viewed

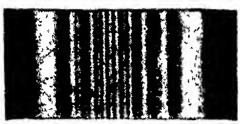
TYPICAL INTERFERENCE PATTERNS



DIFFRACTION OF ELECTRONS



DIFFRACTION OF X-RAYS



VISIBLE LIGHT

FIGURE 38. Interference effects are a test for *waves*. (Adapted from Hausmann and Slack's *Physics*.)

at an angle for which that condition is satisfied. If the path-difference is such as to destroy or weaken *red* by interference, blue will predominate. Thus the colors of soap bubbles, and thin films in general, are understood.

The exact agreement of optical interference effects with the results predicted by an analysis of wave motion establishes the vibratory, or wave, character of light with mathematical certainty. The wave lengths of all the colors of visible light, small as they are, are measured so accurately that the standard meter has been re-defined in terms of the number of wave lengths of a certain green light that must be laid end to end to make a meter; and by suitable means the wave lengths of all the other radiations whose nature is similar to that of light are accurately determined. By results to be considered later, all the radiations of a light-like physical nature are known to be of electromagnetic origin, hence we find in the literature what is called the *complete electromagnetic spectrum.* Arranged in order of increasing wave length, this spectrum contains *gamma rays; x-rays; ultraviolet; visible light* (violet to red); *infra-red* (heat) radiation; and *radio waves,* both short and long. Many practical details concerning some of these radiations will appear in the next unit; but here we are primarily interested in one fact. Light is not a corpuscular radiation of the sort that alpha or beta rays are; it is a wave motion produced by the vibrations of the electrically charged particles of which matter is composed; and it is propagated through empty space at the highest speed ever measured. The vibratory character of the light disturbance cannot be doubted; but how this wave motion is propagated through empty space will seem to be an unsolvable conundrum to all who insist on mechanical models for their thinking. To these, light must seem, as Dr. Lemon has remarked, to be a wave motion without a waver.

Light Energy Is Also Atomic

We have not finished with the amazing characteristics of light. Although light certainly possesses the vibratory properties of wave motion, it also behaves in some respects exactly as corpuscles do. We have already proved that both matter and electricity are atomic in the sense that they are composed of small fundamental unit quantities. They are discrete or discontinuous, not continuous like space and time. *In that same sense, light energy is atomic.*

Consider the photoelectric effect. Light falls on a suitable surface. Zinc, sodium, potassium, cesium, or certain other materials will do if visible or ultraviolet light is used, and any material will exhibit the photoelectric effect under the action of x-rays. The sensitive surface emits electrons when light strikes it. Here is another means of getting electrons out of matter. In the Coolidge x-ray tube and in radio tubes heat is used to evaporate electrons. In photoelectric cells, the so-called electric eyes, we drive the electrons out with beams of light. Thus, as we shall see in a later chapter, handy light-measuring instruments are obtained, machinery can be controlled automatically by beams of light, television and talking pictures become possible.

Light is a wave motion. Ripples spreading out from a pebble dropped into a calm pool give us a picture of *continuous* wave motion. There are no gaps along the crest of a water ripple. If light waves were continuous, all the atoms in the surface layers of the photoelectric substance would be bathed equally. Every atom would receive only its fair share of the light energy. Investigations show that it *is* the energy of the light, not of the atoms themselves, that is converted into the energy of the photoelectrons which are shot out. If the light performed merely a trigger action, as in a gun, the atoms themselves furnishing the energy, the

ejected photoelectric emission would not depend, as it does, on the energy of the light that causes it. The energy of a rifle bullet is not determined by the vigor with which the trigger is pulled. The energy of the photoelectrons, however, comes from the light; yet accurate measurements prove that if the light waves were continuous, so as to bathe all surface atoms equally, an ordinary illumination would need to shine steadily on the sensitive surface for *months* in order that a given atom might store up enough energy, by hoarding its share, to emit an electron. Actually, the expulsion of electrons occurs as soon as the light strikes the surface. There is no delay at all. Evidently, a few of the atoms receive far more than their fair share of the light energy, some none. This being true, the light cannot be continuous. It must consist of small packets of concentrated energy. In this sense light energy is atomic, not continuous. The same fact about radiant energy was deduced by Max Planck indirectly, from the results of his study of heat radiation. Thus one hears of the quantum theory of radiation. An atom of radiant energy is called a *quantum*. If the energy is light, the atom of energy is often called a *photon*. The important fact here is that we find *energy* displaying a property of *matter*.

Other experimental findings confirm this remarkable similarity of matter and radiant energy. For example, light exerts a *pressure* on surfaces when it strikes them. Very delicate systems have actually been set into motion by the pressure of light, *pushed* as if by a very feeble breeze of matter. The same conclusion is reached through a discovery which won Arthur Compton the Nobel physics prize in 1927. When a beam of monochromatic x-rays (all of one wave length) strikes the atoms of one of the lighter elements, such as carbon, *two* monochromatic beams of x-rays result. One beam has the same wave length as the original,

the other a greater wave length. The increase of wave length of this second beam (the Compton effect) can be shown to correspond to a decrease of energy of the individual packets of energy (quanta or photons) which compose the beam. *The photons rebound from the atoms with less energy than they had when they struck!* They give some of their energy to electrons (which are emitted) and rebound with correspondingly lessened energy themselves. The important fact is that here we find packets of x-ray *energy,* a wave motion, rebounding like particles of *matter.*

Conversely, beams of high-speed electrons, which admittedly possess those two attributes, inertia and corpuscularity, which until recently were regarded as sure signs of materiality, have been found to produce *interference patterns* resembling those obtained with light. Thus not only does light show some of the properties of matter; but the particles known as electrons manifest some of the properties of a wave motion, light.

The gradual breaking down of the distinction between matter and energy is one of the most significant results of modern research. Another observation bearing on this question should be cited. When the sun is eclipsed, so that we can see the stars beyond it, we find that starlight passing the sun is deflected towards it, as if subject to the same gravitational attraction that acts on ordinary matter! What is the law of gravitational attraction? The force is proportional to the product of the *masses.* . . . Does light energy possess mass? Or are energy and mass two aspects of one fundamental reality? Note that we are presenting facts, but the conclusions we draw are stated tentatively. The plain truth is, that ordinary language of the sort that arouses images in the mind fails us when we face the ultimate mysteries of reality. Mathematics does not fail us, and apparently the basic reality at the bottom of everything physical can be expressed only in

mathematical terms, not pictured. But at least we are seeing a few of the reasons why man has been forced to give up the naive ideas of reality which his ordinary experience suggests. The analytical mind has left the senses far behind.

Is Materiality a Result of Energy?

As we near the end of our discussion of the nature of matter and energy, let us revert to a question which was raised far back in the unit, a question which may have sounded rather crude: Is matter something which has energy, or is energy something that has matter? We have found that matter is atomic, that electricity is atomic, that light energy possesses the characteristics of both wave motion and atoms—and we have found that matter and electricity are so intimately related that they might easily be different aspects of the same thing. Further, we saw that the charge of the electron is so great, in proportion to its mass, that apparently the electron is at least very nearly pure electricity.

Now, the criterion of what we ordinarily call matter is *mass,* and mass is measured by *inertia.* The mass of an electron has already been stated—but that was the mass found by studying electrons which were moving at relatively small speeds as compared with that of light. Studies of electrons shot from radium at very high speeds—the beta rays—have brought an amazing additional fact to light. The electric charge of the electron apparently remains constant at all speeds, but its mass grows greater as the electron moves faster!

For instance, at low speeds the mass of the electron has the value which we gave earlier. At a speed which is eighty percent of that of light the mass is fifty percent greater than the low-speed value; at 93 percent of the speed of light the mass is twice its

original value; at 97 percent of the speed of light the mass is two and a half times its original value. The law of the effect is such that there is an enormous increase of mass at the highest speeds, the mass becoming infinitely great at the full speed of light. Thus the very act of speeding up an electrically charged particle makes it harder to speed up. The particle offers a greater and greater inertia, or resistance to acceleration, until at the speed of light it would be infinitely hard to accelerate and thus could not be made to move any faster no matter how great a force were applied.

This amazing discovery necessitated a radical revision of earlier ideas of mass. The reader has already grown accustomed to the idea that the *weight* of a body depends on where it is, being only one-sixth as great on the moon, for example, as here at the surface of the earth. Weight is what we notice when we lift a stone; but mass, or inertia, is what we notice when we kick it along the ground. Never yet in our pages have we considered the possibility that mass, or inertia, which by ordinary observations seems to be the most fundamental measure of the amount of matter in a body, might itself be a variable quantity. Yet here we have experimental evidence showing that, at least when small electrically charged particles are involved, the mass depends on how fast the particle is moving. If this effect were noticeable at low speeds, the shopper would find her bag of sugar getting heavier when she started her automobile to take it home. To pursue this result further would carry us deep into the realm of relativity, an intricate though fascinating subject which we are resolutely reserving for a few remarks in the concluding section of our book; but there is one conclusion which seems strictly relevant to our present inquiry.

The particle gains energy as it gains speed. It also gains mass, as we have just seen. Is not this extra mass, then, a manifestation

of the extra energy? And if part of the mass is really energy, may not the whole mass be energy?

Remember that already in these pages we have been led to the idea that electricity is more fundamental than matter. We drew that conclusion, tentatively, from the fact that there is only one elementary quantity, or amount, of electricity, but there are 92 elementary atoms. That was not proof, merely a reasonable inference. Later, we found the idea strongly supported by the enormous preponderance of the electricity of an electron, as compared with its mass or inertia. Now we have, in this variation of mass with speed, a further indication that what we recognize with our senses as matter, something material, a brick or a stone, may actually be that mysterious entity, energy, in one of its many guises. This is the explanation of our earlier statement that the two principles of conservation — of matter and of energy — now seem to reduce to one; and it is also what scientists have in mind when they estimate how long the matter now present in the sun will last if the sun keeps on radiating its own substance away as energy.

The Structure of Atoms

The facts presented in the last few pages suggest that the interior of an atom cannot be pictured as concretely as the mechanical-minded would wish. We have seen that an atom has parts; that it is mostly empty space; that it contains electricity; and that what we may term (for lack of a better word) the *matter* in it, is distributed at intervals so wide that the atom suggests a solar system in miniature. In the Rutherford-Bohr model of the atom, the analogy to the solar system was carried to the point of picturing planetary electrons as revolving in orbits around a denser nucleus.

When the atom either radiated or absorbed light, the planetary electrons were supposed to jump from one orbit to another. These abrupt jumps would meet the requirement, based on observation, that radiant energy be radiated and absorbed discontinuously, in quanta; and if the orbits were suitably spaced the regular arrangement of bright lines found in the characteristic light spectra of certain elements (also the characteristic x-ray spectra) would be accounted for. The Rutherford-Bohr atom was designed primarily to explain the facts of radiation.

The chemist, naturally, emphasizes chemical combination, the union of atoms to form compounds. The Lewis-Langmuir model has been serviceable in correlating numerous facts of chemistry. In this model, the electrons are arranged around the dense nucleus in such a way as to account for combination. The fact that many compounds, when dissolved, can be dissociated by a current of electricity shows that electric forces must be involved when atoms unite to form compounds. Furthermore, the facts of *valence* need to be interpreted. In hydrochloric acid (HCl), for example, *one* hydrogen atom is combined with one atom of chlorine; but in water (H_2O) *two* hydrogen atoms are required to satisfy one oxygen atom. Hydrogen is said to be *monovalent*, oxygen *bivalent*. Chlorine has a valence of one, the same as hydrogen, since one atom of chlorine combines with one atom of hydrogen. A convenient measure of valence is the number of atoms of hydrogen or of chlorine with which one atom of the element in question combines. In the Lewis-Langmuir model, the electrons are arranged in shells around the denser nucleus. Neon, which forms no known compounds, is pictured with eight electrons in the outer shell. This, supposedly, is the maximum number possible—hence the neon atom contains no unfilled gaps in the outer shell where electrons of other atoms might attach themselves. Thus

its lack of chemical activity (zero-valence) is accounted for. The sodium atom contains, according to this theory, one electron in its outermost shell, with room for seven more; the chlorine atom contains seven, with room for one more. When the two atoms unite to form one molecule of common salt, the one outer electron of sodium is pictured as filling the gap in chlorine's outer shell. The sodium atom loses an electron and becomes positively charged; the chlorine atom gains one electron and becomes negatively charged. The two atoms are then held together in chemical combination by the force of electric attraction. Unlike charges attract each other. Similarly, other compounds are interpreted; also the regular grouping of the elements according to *valence, atomic weight, atomic number* and *other chemical properties,* in the *periodic table* which is given in the appendix.

Both models have been useful in correlating observed facts and in suggesting fruitful researches. The Rutherford-Bohr atom pictured commonplace matter, say a spoonful of table salt, as a collection of billions of miniature solar systems in orbital motion; and the Lewis-Langmuir model presents the intriguing idea that electric attraction alone keeps the atoms of the two elements, sodium and chlorine, the one highly corrosive by itself, the other poisonous, safely joined together in that spoonful of salt. But each model presents certain inconsistencies, and neither accounts satisfactorily for all the marvelous phenomena of matter. Too simple and too concrete to be accepted as reality, both models may be regarded as intellectual conveniences. Matter and energy are, as we have seen, not nearly as sharply differentiated from one another as was once believed. They apparently merge into one fundamental reality. Since an entity of such a nature cannot be pictured, there is no longer any reason for trying to picture the atom more concretely than as a rather vaguely defined system of

shells of energy surrounding, at relatively great distances, something that is very highly concentrated. The facts which we have reviewed, together with a wealth of other evidence obtained through spectroscopic studies of x-rays and light, show that much very clearly; but to try for a concrete picture of something in which matter itself seems to dissolve into energy, and vice versa, is to attempt the impossible. When we reach the core of physical reality, the truth is presented in mathematical equations, not pictured.

But the existence of a concentrated nucleus far inside the outer portion of the space which an atom occupies cannot be doubted. Experiment has shown this in a striking manner. Rutherford has shot alpha particles through thin gold foil and observed the directions in which they emerge. Most of them go straight through, confirming the idea that the atoms which they penetrate are largely empty space; but occasionally one is deflected through a wide angle, showing that it has passed very close to the concentrated nucleus. The frequency with which this occurs permits of calculations of the relative sizes of nuclei and whole atoms. Imagine having to do sharpshooting to strike *matter* in solid gold!

There is a relatively dense nucleus of *protons,* positively charged, at the center of an atom; and around this, at relatively great distances, are electrons. These electrons are often called *planetary electrons,* by analogy with the solar system; but as we have seen, the word should not be taken literally. *Extra-nuclear* is a better term. The number of extra-nuclear electrons is the *atomic number* of the element; and the *atomic weight,* relative to hydrogen, is the number of protons which compose the nucleus. Since the hydrogen atom is the lightest and simplest of all, containing one proton and one extra-nuclear electron, and since the nuclei of all other atoms consist of multiples of protons, the atomic weight of

any element, relative to hydrogen, should apparently be a whole number, with no fractional part. Actually, fractions appear in many cases. This apparent mystery has recently been cleared up by the discovery of *isotopes*. The poison gas chlorine, for example, consists of two isotopes having atomic weights of 35 and 37, respectively. If the two were present in equal proportions, the average would be exactly 36; but there is more of the lighter chlorine isotope than of the heavier, and the average atomic weight is 35.46. Many series of isotopes are known. In considering the age of the earth in Chapter 4, we found that the existence of three isotopes of lead, of masses 206, 207, and 208, was a very great asset. Isotopes are elements possessing identical chemical properties but differing in mass. The recent discovery, *heavy water,* has revealed the existence of heavy hydrogen, called *deuterium,* which has twice the atomic weight of hydrogen. Whether deuterium should be regarded as an isotope, in the ordinary sense, is not yet clear. The compound of this with oxygen is heavy water, a substance possessing remarkable properties that may lead to useful applications in medicine.

The heaviest and most complex atom, uranium, has an atomic weight of 228, an atomic number of 92, a nuclear charge of 92. Apparently it consists of 92 extra-nuclear electrons arranged outside a nucleus containing 228 protons and 136 electrons. One whole atom of uranium, as indeed of all elements, contains equal amounts of positive and negative electricity when not ionized, and is therefore electrically neutral from the outside, but exerts electric forces within it. Thus an alpha particle shot through an atom is slowed down by electric forces. The act of ionizing, often referred to in our pages, involves the loss or gain of outer electrons. For example, we have referred to alpha rays as streams of ionized helium atoms. The helium atom contains a nucleus of

four protons and two electrons, and two extra-nuclear electrons. Strip off those outer electrons, and an alpha particle results. When the alpha particle picks up two electrons from the substance which it strikes, it becomes a helium atom. Speaking so definitely of the number of protons and electrons in different atoms may seem to violate our earlier injunction not to picture the atom too concretely, in a mechanical sense; but it is just as much loose thinking to refuse to accept established facts as to carry the interpretation too far. What seems dangerous in this field, in an intellectual sense, is to *localize* the electrons as concrete particles at certain points, or to speak too trustingly of their possible motions within the atom.

In recent work, the nuclei themselves have been disrupted by impacts of high-energy alpha rays. The atomic nuclei of lithium, beryllium, nitrogen and numbers of other elements have been disintegrated, hydrogen being one of the products of the disintegration. The artificial transmutation of elements, the waking and sleeping dream that nourished the alchemists for centuries, is now an accomplished fact. Man has learned to do artificially, what the still-mysterious processes of radioactivity accomplish spontaneously: he takes atoms apart, he transmutes one element into another. How far he will go in coming years in unlocking the atoms, and possibly releasing for practical use their enormous stores of energy, only a rash writer would predict. In 1932 Chadwick in England added a new elementary particle, the *neutron,* to join the select company of the proton and the electron; and in 1933 C. D. Anderson in California discovered the *positron*. The neutron has the same mass as a proton but is uncharged. The positron has the mass of an electron and an amount of electricity equal to that of the electron but of the opposite sign, positive instead of negative. Since the mass of a positron or electron is

negligible in comparison with that of a proton or neutron, it may be that the neutron should be regarded as the essence of matter, divorced from electricity; and that a proton is a neutron possessing either one positron embedded in it, or possibly one positron more than the number of electrons in it. This would give us two separate entities, matter and electricity; but then what of electromagnetic radiant energy — radio waves, heat radiation, visible light, ultraviolet, x-rays, gamma rays — which, as we have seen, possesses many of the properties of matter?

To complete our brief résumé of recent discoveries, in 1934 M. and Mme. F. Curie-Joliot of Paris announced *artificially prepared* radioactive material. In the short space since then, more than fifty of the ordinarily non-radioactive elements, including aluminum and sodium, have been put into such a condition that they continue for seconds in some cases, minutes or hours in others, to radiate spontaneously in the manner of the naturally radioactive substances discussed a few pages earlier. Impacts of alpha particles or deuterons are used to produce this effect. A *deuteron* is the nucleus of heavy hydrogen (two protons); the alpha particle is the nucleus of a helium atom (four protons).

Thus at this moment all the forms of matter that we know — iron, water, rocks, air, diamonds, cats, teacups, everything you can think of — seem to be reducible to four elementary building blocks which are so intimately associated with electricity and electromagnetic energy that distinctions are either vague or irrelevant.

Retrospect

Here we rest our case, for the time being. We have come a long way in our search for the unseen. We have come a long way

from the demons of the savages, from the ocular beams of Plato, the four elements and the quintessence of Aristotle, the philosophers' stone of Roger Bacon, the electric amusements of the Wizard of Wittenberg, the phlogiston of Stahl, the caloric of Lavoisier. For old marvels, new marvels are substituted — and always the truth has proved more amazing than the fancied wonders of the ancients. Some cannon have been bored, a little ice rubbed, chemicals weighed, some air allowed to expand, a little silver stuck on copper in the plating bath. . . . Thousands of experiments — and now we are peering down into the floor we stand on and wondering how those atomic universes of electricity and empty space can support us. Dalton gazed into a pile of salt, a mass of iron, and with his mind's eye he saw atoms. And just as Galle perceived with his eye the planet which had already presented itself to the analytical faculties of Leverrier, so Crookes, an old man staring fascinated into his radium spinthariscope, saw the flashes of the individual atoms which Dalton had already seen with his mind. What now is that chair whose arms we so confidently gripped, what the aroma of the coffee, the drop of blood from the scratch, the cat itself? We look into them and count the shells of energy that make them large. We measure the enormous expanses of empty space which separate that energy from its nucleus. The genius of mind has been operating through the centuries, operating on a material universe so marvelously constructed that surely the reader will pardon the license of that poet who wondered if perhaps man had not unraveled mysteries which he was never intended to solve. A poetic fancy, merely; yet who can chain his own inner poet when he confronts the wonders which modern science has revealed in the three and a half centuries since Galileo climbed to the top of the leaning tower?

Waves that are particles, particles that are waves — and both

so intimately related to electricity that a clear distinction is hard to make! From electrons to stars, from a sub-atomic particle to Antares, within whose hot body the orbit of Mars could be placed with room to spare. . . . Generating electricity by the mere act of separating two kinds of elementary matter from each other. . . . A sun which dissolves in radiation, sending forth its own corporeal substance as radiant energy to warm and light the world. . . . Yes; we have come a long way. But we still have far to go in our present study. We have not delved into the practical applications of energy and matter, we have not watched science at work making a new physical environment in which man can work out his destiny. We want to know the answers to other familiar questions not dealt with yet: what natural agencies, including the weather, are at work changing our environment; how are mountains made, and seas and plains and rivers; what is the history of the earth, what the nature of space and time, how far the outermost galaxies?

A large program — yet even so, where has man still to go? Can one wonder that the leaders of exact science have stood confident as they surveyed the result of their labors, a physics that goes beyond and behind the imagined metaphysics of the ancients yet works in a workaday world? Can one wonder that they look ahead expectantly to a day when their own remaining problems will be solved, or why they gaze eagerly, sometimes impatiently, towards a long-delayed dawn that will bring the answer to greater mysteries still: the inner nature of man, what life is, what that creative genius which has penetrated the core of inanimate nature yet does not know itself — and how it can be that a race of beings who count electrons and write impartially the equations of dynamos or distant stars can fail to grasp in the fullest measure the benefits which the almost boundless resources of nature are ready

to pour into mankind's lap under the guiding hand of science? Surely, the reader will not close his mind to the great problems, within and without physical science, which remain to be solved; he will not stand blinded by the successes achieved to date. Standing, perhaps, on the threshold of adult life, with more years ahead of him, according to the insurance man's tables, than the years in which many of the splendid results discussed in this unit have been amassed, how can one ever find time to be bored? Imagination, if controlled by the sure, realistic, analytical thinking which we call exact science, is a mighty force. To stand blasé and bored in this amazing world of men and microbes, electrons and stars — would that be to censure the world, or to confess insolvency within, a bankruptcy of the spirit?

MATERIAL FOR REVIEW AND SELF-QUIZZING, UNIT 2

True-False Review — Appendix, Part 2.

Suggestions for Supplementary Reading and Reference

The Renaissance of Physics — Karl K. Darrow (Macmillan)
A History of Science — Sir William Dampier (Macmillan)
From Galileo to Cosmic Rays — H. B. Lemon (University of Chicago Press)
General Chemistry — James Kendall (Appleton-Century)
The Spirit of Chemistry — Alexander Findlay (Longmans)
Makers of Chemistry — E. J. Holmyard (Oxford University Press)
A History of Experimental Physics — C. T. Chase (Van Nostrand)
The History of Western Civilization — H. E. Barnes (Harcourt, Brace)
A History of Philosophy — Frank Thilly (Holt)
Science and the Modern World — A. N. Whitehead (Macmillan)
Electrons (+ and —) — R. A. Millikan (University of Chicago Press)

UNIT 3

THE CONTROLLED CHANGES, OR FORCED EVOLUTION, OF OUR PHYSICAL ENVIRONMENT

Chapter 11

SCIENCE AND INVENTION

Coming now to the third major division of our study, we turn from the philosophical to what, for lack of a better word, may be termed the practical aspects of modern physical science. At the mention of the word *practical* there springs to mind a host of inventions which have reached into our lives and changed the fabric of modern civilization. Communication, transportation, entertainment, manufacturing, home-making, agriculture, war — where will one find a phase of present-day civilization which has not been transformed by science and invention?

As we approach what we have loosely called the practical, the reader of one turn of mind may expect to plunge immediately into the specifications of dynamos, engines, motors, gears, refrigerators, transformers, lamps, telephones, spectacles, telescopes, color cameras, radio sets, television apparatus, photo-electric relays, sound movies, air-conditioning installations, dictaphones, sound-proof studios. Another reader may anticipate the technical details of the manufacture and applications of acids, drugs, dyes, alkalis, fertilizers, perfumes, explosives, fuels, soaps, building materials, colloids, plastics, metals, fabrics, photo-chemicals, refractories, alloys, paints, poisons, foods, cements. Some may be looking for descriptions of boilers, plumbing, hot-water systems, furnaces, fire extinguishers, hydraulic jacks, turbines, smelters, pumps, airplanes, mechanical cotton-pickers, the textile-maker's loom, the best way to open tin cans, how to remove ink spots.

Applied science has something to say on all these subjects, and on many others.

Meaning of Practical

When faced with the task of selecting from whole libraries of material, it seems wise to take a moment to see where we are in our present study and to decide upon our objectives. Just as the tourist finds his trip more enjoyable if he consults his roadmap occasionally, not to mention the greater probability of reaching his destination, so we pause at intervals to survey our progress and to plan our future course.

In one sense of the word, all our work up to this point has, we hope, been practical. Robert Louis Stevenson said that the happiest person is the one who knows the most interesting things to think about. If one accepts the half-truth contained in this sweeping exaggeration, anything is practical, or useful, which is interesting; and surely the objective sought in our first unit — an understanding of the solar system, its relation to the universe of stars, and our own physical relation to the whole — helps to make life both interesting and significant. In our second unit we came a little closer to the common meaning of the word *practical;* for although our practical illustrations there were merely incidental to an attempt to reach a sound philosophical comprehension of the nature of physical reality, we must accept the fact that man's successful investigations of that problem have enormously accelerated the pace at which science contributes the devices and methods which daily affect our actual operations of working, eating, traveling, communicating and enjoying ourselves. In the long run, the abstruse mathematical developments of the theory of wave mechanics now in progress may be fraught with graver practical consequences for humanity than the approaching commercialization of television or rapid trans-oceanic passenger flying.

We shall adopt a middle ground in defining *practical.* Without

going to the justifiable extreme of calling all knowledge practical, we shall stress the science behind those inventions and processes by which science is applied in daily life, rather than the devices themselves. One wanting to repair his own radio will need to seek

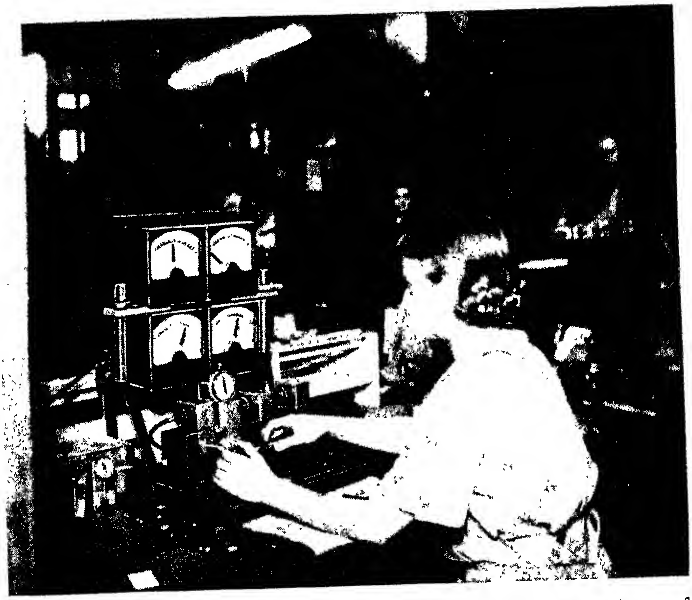


FIGURE 39. A practical operation: checking the dimensions of shafts. Four electric gauges magnify a variation of 0.0001 inch to give a half-inch movement of the instrument pointers. (Courtesy General Electric Company.)

additional information outside our covers. Assuming a normal curiosity concerning the physical actions which touch us most immediately, we seek not so much certain technical skills as to broaden our outlook on our actual environment.

Our criterion, then, is *immediacy* — immediacy of effect and interest. It may not be entirely true, of course it is not, that, in Ribot's suggestive phrase, the world we live in is the condensed

imagination of man; but certain it is that our environment is to a great extent man-made. Where one lives determines how the responsibility is to be apportioned between natural and artificial evolution, if we may use that word in a physical sense. To one who lives in a great metropolis, where even the stars are seldom seen, the surroundings are largely man-made; while the worker of an old-fashioned farm in a remote and sparsely settled region finds unaided nature more largely responsible for his physical environment. Yet even that remote farm home may house a radio, electric lamps, a gasoline engine, a motor-driven pump.

Thus our underlying theme in this unit is to be the artificial or man-made modifications of our physical environment, and some effects of those modifications; while in the succeeding unit we shall be interested in the natural changes caused by the weather, geological actions, etc. The two units now getting under way may, in a sense, be balanced against each other, this present one dealing with what may be called *forced evolution* in the physical domain, the next with *natural evolution* in the same sphere. The reader is asked to note that we are using the word *evolution* in its general sense, not the technical biological meaning.

Science Distinguished from Invention

In the past, the discoveries of science have usually been applied through the intervention of engineers and inventors. Pure science is science seeking truth for truth's sake, an end in itself. Applied science is science working towards a goal set, not by itself, but by others. Engineers and inventors are traditionally the middlemen between science and society at large. All true engineering is based on science and springs from it. Invention may, or may not, be based on science. A great many useful inventions often

incorrectly attributed to science have been the products of sheer ingenuity, or, as Sir Oliver Lodge put it, of men thinking with their fingers. In such cases, the responsibility of science has been merely that of having contributed to the intellectual climate of the age in which the inventor worked, and to the store of materials and processes available at the time. The printing press, the cotton gin, the sewing machine, typewriters — these contributions to civilization, although obviously they obey the laws of physical science and owe a debt to it, are to be classed as inventions rather than scientific discoveries.

The development of radio communication furnishes an interesting example of the interplay between science and invention. In 1864, as the American Civil War was drawing to a close, James Clerk Maxwell, the celebrated British physicist, announced the electromagnetic theory of light. Maxwell was born the year Michael Faraday discovered electromagnetic induction, the principle applied in generating all the electricity that flows through the great power lines of the world, and he built on Faraday. Examining the laws of electricity and light which were known to him, and combining them in a notable mathematical advance, Maxwell not only deduced that light is an electromagnetic effect, but he wrote out the mathematically correct laws which govern the propagation of electromagnetic waves through space. Here was a development in the field of pure physics which outshone Leverrier's successful calculation of the position of a planet hitherto unknown to man. At one stroke Maxwell swept the physics of light into the science of electricity, thus establishing a tremendous advance towards the unity of thought which will no doubt pervade all sciences when we learn enough. In addition, he not only implied the possibility of sending electromagnetic waves from one place to another without benefit of intervening

wires, but he stated the speed with which those waves would travel and published the exact and general laws describing their propagation.

It may be difficult for the reader, who, like all the others of us, cannot comprehend the intimate history of genius unless, perchance, he is one himself, to understand how a great scientist, holding in his hands a potential development capable, as we now know, of saving countless thousands struck down by disaster on land or sea, a new agency destined to change man's thinking and daily customs on a world-wide scale, to extend the power of personality until it encompasses the globe with an immediacy of effect undreamed of by the Caesars and Napoleons of yesterday — in short, how a mind capable of making the original great discovery could fail to set to work at once to realize the latent possibilities of his discovery for the benefit of mankind. Yet Maxwell lived fifteen years longer without trying the experiment, and eight more passed by before his new principle was tested experimentally and what we now call radio waves consciously and purposely produced for the first time in history.

Heinrich Hertz did this in 1887, a young German physics professor working at Carlsruhe as lecture demonstrator to the great von Helmholtz. His mentor suggested the attempt to realize Maxwell's work in actual experiment, Hertz tried it, and radio as an experimental study was born. The work was still pure science; for the records indicate that Hertz himself, though actually producing waves with his sparking apparatus and seeing another spark-gap across the laboratory flash out the news that Maxwell had been right, did not appreciate the practical possibilities for mankind inherent in his success. But down in Italy, Guglielmo Marconi heard of Hertz's work. Marconi began experimenting in his father's garden, and soon he was in England securing gov-

ernmental assistance in a project which unrolled itself before his mind's eye in breath-taking grandeur. In 1896 commercial wireless telegraphy became a fact in England, the work of Marconi the *inventor;* in 1900 the first ship in distress at sea was saved by radioing signals of its plight; in 1901, on December 12, transatlantic wireless telegraphy by dots and dashes was realized when Marconi in Newfoundland detected three feeble clicks signifying that the letter " S " had traversed the Atlantic on waves generated 2000 miles away in Cornwall, England. That lone " S," coming across the ocean with the speed of light, influenced the reader's life whether he uses a radio or not — and possibly the destinies of nations yet unborn.

Other men, both scientists and inventors, played important parts in Marconi's success; but if one is to remember three names in this field, they must needs be Maxwell, Hertz, Marconi. Thomas A. Edison's earlier discovery (1884) of the leakage of negative electricity from a hot filament to a metal plate across a vacuum now led to the thermionic valve of Sir John A. Fleming, which made radio telephony, the transmission of voice, possible; and in 1907 the American, Dr. Lee de Forest, added the third electrode, the grid, thus bringing to radio telephony not only improved voice reception but — a new factor — amplification as well. This was briefly discussed in Chapter 9. Thousands of patents have been filed on various aspects of radio, and numerous scientific discoveries have contributed towards the present state of development; but we leave the topic temporarily, for our purpose was to contrast the roles of science and invention. These steps can be distinguished in the history of radio: pure *science; invention;* a *hobby* enlisting the spare hours of amateurs by the tens of thousands, some of whom contributed useful improvements; professional *engineering* and commercial *investment;* finally, an ac-

cepted *service* of daily life, a process still evolving but ready to be judged by its effects on life, without benefit of the early wonder that the seeming miracle should be.

Possibly, somewhere in the literature of pure science, there exists today some overlooked bit of knowledge pregnant with comparable possibilities for mankind. Possibly; but not as probably as in Maxwell's time. The gap between science and invention has steadily narrowed, until today the two are closely, sometimes inextricably, related. Many discoveries and inventions immediately applicable to the practical world of affairs now arise yearly in the research departments of universities and colleges; and in the splendid laboratories of the General Electric Company, the Bell Telephone System, the duPont chemical works, and many others, pure science, engineering and invention are cooperating directly. The result is a mass production of technical ideas such as the world has never known before. Less and less grow the chances of the inventor who depends on what Lodge, himself both scientist and inventor, called thinking with the fingers. True, just as science today cannot predict which isolated hamlet, which pine in all the world will be the next to be visited by lightning, so none can know where the next bright flash of the inventor's genius will occur — but today the isolated inventor, once he shows the color of his metal, is usually absorbed into a laboratory where he finds the ready cooperation of science and engineering to perfect and extend his ideas.

If the reader who feels within himself or herself the first pleasurable stirrings of inventive genius hopes to enjoy the thrill of realized creation, recourse to solid science far beyond the contents of this introductory survey is recommended. It is not the principal purpose of science to train inventors, indeed the original thinker stands out in science as in all walks of life; but the wise

candidate for service will accept all the cooperation the age affords. Even cooperation can be overestimated. Necessary as cooperation is, a virtue which must be realized more fully still if civilization is not to perish, we should recognize that new ideas seem to be the work of individuals. Here we tread debatable ground. Once his imagination has functioned, the original thinker will find many persons who seek to change his *I* to *we* or *they* — but let us accept the individuality of the creative imagination, one mind *thinking*. One speaks with trepidation here; for none knows what the creative imagination is, or how it functions. Suddenly a new idea simply is — and often the vehicle that brought it cannot trace its origin, himself. Studying the sleeping habits of inventors is not likely to solve the mystery. For the present, we can read the French psychologist Ribot's inspiring work, *The Creative Imagination*. Ribot seems to have felt at some time the quick, sharp, almost painful ecstasy of creation, and so passed the first qualification for talking about it. This may sound unscientific, as if implying that, in another field, one must needs become an electron to discover how it acts. Let us leave this intriguing bypath, which it would be presumptuous to pursue farther. To find what happened within Maxwell or Marconi when a new idea was born would be worth any reader's lifetime. Physics, chemistry, biology, psychology, mathematics, and the elusive spark of genius itself (for genius has a right to be judged by its peers) would all be needed — and the answer must likewise explain Grieg, Shakespeare, Plato, and creative thinkers in all walks of life. Is it too much to hope? To capture an idea, bridle it and stand it there, ready for the world to ride, is something to look forward to.

Consequences of Invention

But science has bridled so many ideas that the social and economic scene has grown enormously complicated. The air is full of clamor. Books pour from the presses. *Men and Machines, Technics and Civilization, The Frustration of Science, Science for a New World* — one could make a long list of recent titles. Despite our just distinction between science and invention, science must brace its shoulders to receive the responsibility of having at least contributed the knowledge which made this technological civilization possible. A student of science should be aware of the discussions now waging concerning the role which science plays in society at large. However interested we may become in the facts of science and in watching the great discoverers at work, however rightfully we glory in the personal achievements of individual scientists and inventors, one can hardly remain indifferent to the social and economic problems which arise as new inventions appear.

Within the past century, but most notably in the last fifty years, the mechanization of civilization has progressed with ever-increasing rapidity towards a goal not now foreseen. Not only has the production of goods been speeded up, but, as was suggested in an earlier passage, mass production of practical *ideas* has resulted from the continually improved cooperation between science and invention. One discovery suggests another. One wonders if the production of history itself has not been speeded up. Not again is an American general likely to fight a battle on a January eighth in ignorance of the fact that the peace treaty ending the war had been agreed to the preceding Christmas eve. American villages have heard the voices of foreign statesmen not a fraction of a second later, but a fraction earlier, than did the outer fringes of the audi-

FIGURE 40. This battery of ponderous units for grinding and polishing plate glass had to be *invented.* Invention often provides the transition from pure science to practical applications. (Courtesy Pittsburgh Plate Glass Company.)

ence which saw the speaker standing there in Europe on the rostrum. Soon we may see them with the same immediacy, and they will need to consider their facial expressions as well as the words they utter for our consumption. In this age of swift communication and transportation, what happens in one part of the world is quickly known around the globe, and the results are not long delayed. Formerly, when science and industry and, yes, history itself, were being built up slowly and painfully by small discrete populations, life was like an unfinished novel, which one put down perforce without knowing the outcome. The Mayas could build their civilization and vanish unknown to the world, and Maxwell's laws of radio, as we have seen, could lie fallow for many years. Things move faster nowadays. Two young men, working out a thesis in a Scandinavian university, hit on a new way to make ice, and the ink is hardly dry on their academic certificates before American housewives by the thousands are freezing their ice cubes with a little gas flame. A small thing, perhaps, to the philosopher — but a sign of the trend. History is on the march, and what a run for its years this generation gets in a lifetime! What is troubling the leaders is whether man will grow in judgment and in spiritual power to keep pace with science. There are some who, wearying of uncertainty, propose that science should step out of its laboratory and take a hand in determining how the matter and energy whose laws it knows so well should be applied for the benefit of humanity; and there are others who point out very quickly that to attempt to do so would sacrifice the chief tool with which science has wrought its wonders — impartiality and objectivity, the unbiased pursuit of truth. We leave the problem to statesmen and other practical philosophers, while we go on to consider some of the science which underlies our practical, workaday world.

Chapter 12

THE WORLD'S WORK

During the World War, when for many months the sinking of ships by German submarines seemed likely to starve the British population into submission before the British blockade could do the same for the Germans, the Food Committee of the Royal Society of England made very careful studies of the energy requirements of workers in different occupations. The average man employed as a tailor was found to require 2,750,000 calories of food daily; a man engaged in the vigorous work of chopping down trees, 5,500,000 calories; and between these, in order of increasing requirements, were ranged bookbinders, shoemakers, carpenters, painters and stonemasons. The average arrived at for adult men working with hands and legs was a daily ration of 3,300,000 calories, *or 3300 of the larger units used in books on dietetics,* which are really *kilogram-calories.* This is about the rate at which a 150-watt lamp consumes energy.

The Energetics of Civilization

A moment's reflection shows that man, as a source of motive power, is of nearly negligible importance in modern civilization. A sedentary man needs about two-thirds as much energy as the average manual worker, or approximately a million calories *less* per day. For women, changing from a life of active work to a sedentary regimen reduces the food requirement from about 2,650,000 to 2,100,000 calories, a decrease of nearly half a million. These figures make it obvious that even the small wattage of the

human being is largely consumed merely in staying alive. Striking a mean between the million and the half-million, we obtain a figure of 750,000 calories as a very rough estimate of the additional energy required to work instead of idling. If the body's efficiency in using this energy were equal to that of an automobile, an adult would do about as much work in a useful life of thirty years as we get out of five barrels of gasoline, or about forty dollars' worth, including the tax. A man-day at this rate is worth less than a teacupful of gasoline, and filling the car's tank with fourteen gallons gives one the daily working equivalent of an undersized regiment of six hundred average adults.

A glance at a few selected statistics confirms this picture of the extent to which the scientifically engineered applications of natural sources of energy dominate the scene. If we add the figures in the last column, we find that the primary sources of energy listed

PRODUCTION OF CERTAIN NON-OVERLAPPING SOURCES OF ENERGY IN THE UNITED STATES IN 1935

Source	Quantity	Approximate Energy Value
Coal	420,000,000 tons	3000×10^{15} calories
Fuel Gas (natural only)	19×10^{11} cu. ft.	760×10^{15} "
Gasoline (from petroleum only)	60,000,000 tons	630×10^{15} "
Electricity (from water power only)	4000×10^{7} kw.-hrs.	34×10^{15} "

amounted to 4424 million billion calories in 1935. Without complicating matters by considering the ratio of exports to imports, or the use of crude oil, kerosene, fuel wood, windmills, explosives and a number of other sources of energy, we may conclude that the figure given is well within striking distance of the total energy available for doing work by artificial means in the United States

in the year in question. In other words, there is the year's inventory of the major portion of the energy from inanimate sources which was available for heating, lighting, digging, building, refrigerating, transporting, communicating, entertaining, and manufacturing in our country. If the 127,000,000 people who resided in the United States in 1935 averaged — man, woman and child — a daily ration of 750,000 calories for useful work, aside from merely staying alive, the total energy resources shown in the table are considerably more than a hundred times the extra energy-for-work of the population of the country, and more than six times the working equivalent, at the same rate, of all the people in the world. The results achieved by applied science cannot, in the main, be duplicated by manual labor no matter how many workers seek employment; but leaving quality and kind of results out of the question, we see that the *amount* of physical work done by artificial means in the United States in 1935 was about six times as much as the entire population of the world, if they had all been brought here and kept usefully employed at bodily work, could have done for us.

The importance of man as a source of motive power, already slight, seems likely to decrease steadily. Self-respect, if nothing else, renders a human being reluctant to match his day's work unnecessarily against a cupful of gasoline, a small lamp bulb, or a few fragments of coal. There is the rock on which proposals for a holiday in applied science, wistful programs for a return to the good old times, seem likely to be wrecked. None the less, machines do not come into being at the sign of a wand; and, once devised and made, they are not self-sufficient. The steady rise of man to dominance over mere animal force should act as a challenge, not an invitation to rest on the oars. Machines must be operated, plans made, problems solved.

Composition of the Human Body

To do work requires energy. The source may be the helter-skelter motion of molecules, whose kinetic energy is heat. It may be something else moving: wind, water, electrons. It may be fuel or explosives to release chemical energy and make something move. Viewed as agencies for the conversion of energy, plants and animals are unique in their ability to use themselves for fuel. The fueling of man so that he can live and work is, therefore, a matter of supplying both energy and replacement materials.

So far as replacement of matter is concerned, the composition of the human body sheds light on the materials needed. Three elements — *oxygen, carbon* and *hydrogen* — comprise 93 percent of the compounds found in man. Their proportions by weight, in the order named, are 65, 18 and 10 percent. These elements are of primary importance and, fortunately for man, are very common. Oxygen occurs free in the air and, in combination with hydrogen, in water. Carbon, though abundantly found in indigestible forms such as coal, is present in the air combined with oxygen in carbon dioxide, which through the mediation of plants becomes available for man. Carbon figures so prominently in plant and animal life that the study of carbon compounds is known as *organic* chemistry. The extent and importance of this branch of chemistry may be judged, not only by the fact that the problems of plant and animal nutrition lie largely within it, but also by the great number of organic compounds known to chemists. About a quarter of a million such substances can now be identified. This is five times the number of all other known compounds. Table salt ($NaCl$), water, iron rust (ferric oxide), hydrochloric acid, caustic soda ($NaOH$), are familiar *inorganic* compounds.

Three additional elements account for six percent of the human

body, bringing the total to 99 percent. These are *nitrogen, calcium* and *phosphorus,* which comprise about 3, 2, and 1 percent, respectively. Nitrogen forms four-fifths of the atmosphere, but is so inactive, or inert, that it must be combined with other compounds by the special means afforded by certain plants, or by artificial processes, in order to become available to man. Nine additional elements found in compounds in the body are, in order of decreasing percentage, *potassium, sulphur, sodium, chlorine, magnesium, iron, iodine, fluorine,* and *silicon.* These nine together form only about one percent, and the last three are present in barely identifiable traces.

Food to supply energy and to replace these materials as they are exhaled, evaporated, excreted is of several sorts—plant, animal, and to a slight extent, mineral—but the diet of animals takes us back to plants, hence agriculture remains the basic industry. Growing is a series of chemical actions facilitated (and complicated) by an unexplained something called life. At this point the reader may find it useful to go back and reread Chapter 7, in which we introduced molecules and atoms and gave the proofs for the atomic theory of matter. No physical action is more important than the rearranging of atoms to form different molecules. Without this action, plants, animals, food, and our friend, the man next door, would not exist. What are the actions which produce the marvelous phenomena of growth and bodily energy?

Some Chemical Aspects of Plants and Men

The green leaves of vegetation contain minute globular bodies called *chloroplasts,* whose diameter is about five wave lengths of violet light. Despite their small size, the chloroplasts hold man's fate in their hands; for without the *chlorophyll* which they con-

tain the sunlight would not be stored as chemical energy to enable man and beast to maintain the vital temperature and to work. Food, wood for lumber, and the raw materials of scores of industries would be lacking. Plants feed on carbon dioxide (CO_2) and water (H_2O) obtained, directly or indirectly, from the atmosphere, and on a number of inorganic compounds found in the soil. Carbon dioxide comprises only about one-twentieth of one percent, by weight, of the atmosphere; yet this small amount is the source of all the *carbon* found in vegetable matter. Plants are remarkable for their ability to utilize relatively simple inorganic compounds to yield the more complex molecules which so largely form our food. Carbon dioxide is not only of no immediate use to the human body, it is something which must speedily be gotten rid of; and water, though the most abundant compound in the body, a valuable solvent and of course vital to health and comfort, is not a substance from which the human organism can derive energy directly. Yet plants, through the intervention of chlorophyll, transform these two substances into *carbohydrates,* which eventually supply our bodies with solar energy in highly usable form; and, as if that were not enough, the plants yield free oxygen as a waste product, thus helping to maintain the atmospheric supply of this indispensable but highly active element.

The breathing of all animals contributes to the supply of the carbon dioxide which vegetation needs. The decay of animal and vegetable matter promotes the same end, and so does the combustion of fuels in homes and factories. More than a billion tons of coal is burned annually in the world. The principal reaction in the combustion is,

$$C + O_2 \rightarrow CO_2 + 97{,}000 \text{ calories.}$$

Since the atomic weights of carbon and oxygen are 12 and 16, respectively, this means that 12 grams of carbon unites with 32

grams of oxygen to yield 44 grams of carbon dioxide and 97,000 calories of heat. Thus for every 12 grams of carbon burned, 44 grams of carbon dioxide is formed, and the world's annual burning of considerably more than a billion tons of coal, which is largely but not entirely carbon, yields nearly four billion tons of the gas which plants so urgently require. This is merely a sixth of one percent of the amount of carbon dioxide in the atmosphere. The decay of organic matter is a more important source.

Plants themselves liberate some carbon dioxide when in darkness; but the amount they absorb in sunlight exceeds their nocturnal yield. Since their role in respect to oxygen and carbon dioxide is the opposite of man's, plants and animals together form a balanced system. Precisely how the chlorophyll utilizes radiant energy to turn carbon dioxide and water into useful organic compounds is not understood. The process, known as *photosynthesis,* has not been duplicated in full in the laboratory. The first step, apparently, is the formation of *formaldehyde* and *oxygen:*

$$CO_2 + H_2O \rightarrow HCHO + O_2$$

The oxygen can be seen bubbling upwards from plants submerged in clear water and exposed to sunlight, and can be collected by inverting a glass jar over the plant. From one to two hundred square yards of leaf surface working through the growing season may be required to balance one man's consumption of oxygen for a year. The HCHO, or CH_2O, is the formaldehyde, a colorless, pungent gas which dissolves readily in water. This is the simplest carbohydrate. Formaldehyde has been detected in plants. Great quantities of formaldehyde obtained by other means are used in industry in the manufacture of bakelite by reaction with carbolic acid; and formaldehyde is also employed to preserve anatomical specimens, and as a disinfectant.

The next step in the plant's action seems to be the formation of a sugar, *glucose,* by the condensation of several molecules of formaldehyde:

$$6HCHO \rightarrow C_6H_{12}O_6$$

The product on the right is glucose (grape sugar). This is one of a number of sweet crystalline carbohydrates known as sugars. Carbohydrates taken into the body serve as fuel, and are also partially transformed into fat. *Sucrose* (cane or beet sugar) is an example of another kind of sugar; its formula is $C_{12}H_{22}O_{11}$. On comparing this with the formula of glucose in the equation, we see that they are both composed of carbon, hydrogen and oxygen, but in different proportions. Glucose is present in honey and in the juices of ripe fruits; sucrose is extracted from sugar beets and sugar cane. A mixture of glucose and another sugar known as *fructose* is preferred in making many candies; the two sugars interfere with each other's crystallization, hence the candy remains soft, or " pullable."

Finally, an unknown number x of molecules of glucose come together and undergo a rearrangement of atoms which results in the formation of *water,* and either *starch* or *cellulose.*

$$x(C_6H_{12}O_6) \rightarrow x(C_6H_{10}O_5) + x(H_2O)$$

Some of the water formed by this reaction, together with a vastly greater amount absorbed through the roots, will be evaporated into the air. A large, well-leafed tree may evaporate more than a barrel of water on one hot summer day. This shows the importance of reducing the leaf area by pruning when transplanting shrubbery.

The more complex compound on the right may be either starch or cellulose. The proportions of carbon, hydrogen and oxygen in these two compounds are the same, so that the great difference between them must be due to a different total number of atoms in the

molecules, and to a different grouping of atoms. Here we encounter one of the principal causes of perplexity in the complicated field of organic chemistry. The molecular weights of the two compounds are not known, therefore the number x is not known. But whatever its value, one sees that the chemical equation is *balanced:* there is the same number of atoms of any given element on one side of the equation as on the other, and every atom is accounted for. Otherwise, the law of conservation of mass would be violated. It is not easy to learn *how* the atoms will rearrange themselves in chemical reactions, but if the formulae of the products are known, the filling in of correct numbers to balance the equation is a very simple arithmetical operation. The reader should find it interesting to test every chemical equation that he comes upon, to make sure that it is correctly balanced.

Starch is digestible, a very important food. It is a white, tasteless, odorless carbohydrate produced in abundance by a wide variety of plants, especially cereal grains and tuberous vegetables. Potatoes contain 15 to 25 percent starch. Starch is used in manufacturing glucose commercially, also mucilage. Adding a trace of iodine is a quick test for starch. A compound colored deep blue is formed.

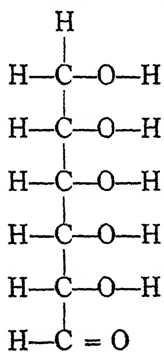
Cellulose, the second possibility in the last reaction, is an indigestible carbohydrate, but in industry is one of the most important raw materials. It constitutes the fibrous structure of plants. Cotton, linen, hemp, flax and wood are largely cellulose. Clean cotton and paper are nearly pure cellulose. It is interesting to note that the action described in our last chemical equation can produce either starch, a fuel for man's consumption, or wood, a fuel for stoves. Owing to the large amount of oxygen already present in cellulose, its heat of combustion is less than that of coal, pound for pound. Combustion, as we have seen, is an *oxidation;*

from that point of view, cellulose may be looked on as already partially oxidized. When one knows that cotton, paper and lumber are largely cellulose, very little need be added to suggest the importance of this plant product. A great metropolitan newspaper may consume more than a thousand acres of forest annually, for the sake of the cellulose. Cellulose is the principal raw material out of which artificial silk, rayon, is made, and is also the basis of many explosives. Since cellulose does not dissolve in a boiling solution of sodium hydroxide ($NaOH$), but wool, a nitrogeneous animal product, does, the adulteration of supposedly all-wool cloth with cotton can easily be detected by boiling a sample in the solution. If the cloth does not dissolve completely, it is not pure wool. Cellulose is not a food, but processes have recently been developed whereby it can be converted into edible sugars. Warming in a dilute solution of hydrochloric acid, or treating with the concentrated acid without heating, transforms sawdust and other cellulose waste into digestible food. Thus our forests, which already bear so heavy a burden in modern civilization, may become an economical source of food as well. Livestock, and possibly we too, may eventually eat them.

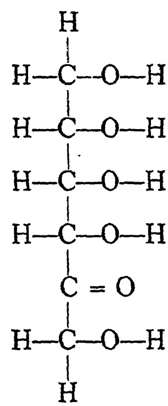
Before leaving the carbohydrates which are formed by plant action, we note that starch and cellulose are good examples of a mysterious class of substances known as *isomers.* The existence of isomers shows that the *arrangement* of atoms in a molecule may be as important as the numbers of the different kinds of atoms. An analysis of starch and cellulose reveals the same elements — carbon, hydrogen and oxygen — in the same proportions, but we have seen how greatly these plant products differ in chemical and physical properties. *Glucose,* the third carbohydrate with which we have dealt, is also an isomer, its mate being *fructose.* Both these sugars are found in ripe fruits, and they have the same

formula, $C_6H_{12}O_6$; but whereas glucose (grape sugar) is sometimes called *dextrose* on account of a certain right-handed optical effect which it produces, the fructose is often referred to as *laevulose* because its corresponding effect on light is left-handed. All we stress here is that two sugars, though identical by the ordinary empirical formula, are actually somewhat different in behavior, therefore isomers. A glance at the *structural formulae* below shows how two isomers can be, in a sense, different compounds, without violating the atomic characteristics of *valence,* which determine how many atoms of a given kind one atom can hold united with itself.

GLUCOSE ($C_6H_{12}O_6$)



FRUCTOSE ($C_6H_{12}O_6$)



The straight lines represent *valence bonds.* We see that every hydrogen atom possesses one valence bond, every oxygen atom two valence bonds, every carbon atom four. The *numbers* of the three kinds of atoms are identical in the two sugars, but the *arrangements* are different. In many cases, structural formulae must be known, in addition to the usual formulae, if the probable reactions of a compound are to be predicted.

And lest we gain the impression that the molecules of these sugars present an extreme of complexity, let us look at the formula of Chlorophyll A, which is one of a number of substances forming chlorophyll in the chloroplasts of plants. The formula is believed to be $C_{55}H_{72}O_5N_4Mg$. Count the atoms in that complex molecule, and speculate on their structural arrangement, which is not known.

The formation of carbohydrates in the leaves of green plants turns sunlight into chemical energy; the slow combustion of carbohydrates in the body frees the energy as heat. When glucose, for example, is oxidized, heat is produced at the following rate:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 677{,}000 \text{ calories}$$

By adding up the atomic weights, one can quickly find out exactly how much of each product is associated with a given production of bodily heat. The atomic weight of carbon is 12, of hydrogen 1.008, of oxygen 16. The term $6O_2$, for example, shows that two atoms of oxygen make one molecule, and 6 molecules are required in the reaction. The only mathematics required is the most elementary arithmetic. Twice 16 is 32, and six times that is 192. Hence the amount of oxygen is 192 grams. The $6CO_2$ term shows that six molecules of carbon dioxide are needed, and each molecule contains one atom of carbon and two oxygen. So we have 12 plus twice 16, or 44, for the molecular weight, and six times 44 is 264. The reaction produces 264 grams of carbon dioxide. Completing the work, we find that *180.096 grams of glucose plus 192 grams of oxygen gives 264 grams of carbon dioxide plus 108.096 grams of water plus 677,000 calories of heat.* Thus the glucose, if completely oxidized, disappears; some oxygen disappears from the atmosphere that we breathe; and in their place we restore some carbon dioxide to the air for plants to breathe, we

evaporate some water from our skins, and we gain a large amount of heat to maintain the bodily temperature and enable us to do work. If the body oxidizes one whole pound of glucose, it gains 1,700,000 calories of heat, about half the daily requirement of energy. This is about 61 percent as much heat as a pound of coal of average grade would yield. Of course, energy requirements are only part of the story, and to concentrate exclusively on a diet of sugar, valuable as it is for giving energy, would be to neglect other important considerations and bring death. Another reaction causes some of the sugar to yield fat in the course of digestion. Fats, like the carbohydrates sugar, starch and cellulose, are composed of carbon, oxygen and hydrogen, but in different proportions.

We have now traced in part the oxygen-carbon-hydrogen cycle of plant and animal processes, and have thus accounted partially for the elements which constitute 93 percent of the body's weight. The remaining elements are also obtained for us by plants, largely from the soil. It would be interesting to treat them all in detail; for recent discoveries in the chemistry of nutrition prove that small traces of certain substances are vital to health. We pass on rapidly — but not without giving special attention to nitrogen, the fourth most abundant element in the human body.

The Fixation of Nitrogen

In 1798 Robert Malthus published his theory that the population of the world would soon outrun its food supply; and nearly a century later, in 1892, Sir William Crookes told the British Association for the Advancement of Science that the world's wheat supply must shortly fail unless chemists found a way to combine atmospheric nitrogen with other substances to form fertilizer

compounds. In addition to oxygen, carbon and hydrogen, farm crops seem to need only ten additional elements: nitrogen, phosphorus, potassium, chlorine, sodium, calcium, magnesium, iron, silicon and sulphur. Fertilizers are valued according to their content of nitrogen, phosphorus and potassium. Growing one ton of wheat robs the soil of approximately 47 pounds of nitrogen, 18 pounds of phosphoric acid and 12 of potash. Despite the magnitude of the nitrogen requirement, despite the steady increase of population, the prophets of scarcity have been confounded. Crops flourish in abundance. Why?

When Malthus voiced his dire prediction (which he based on the birth rate, not on nitrogen depletion) approximately 90 percent of the population of the United States was engaged in agriculture. By the year 1875, the figure had shrunk to 50 percent, by 1930 to 25 percent—and today, although so small a fraction of our population tills the soil, crop *restriction* is a public issue. Chemists have simply followed Sir William Crookes' advice. In 1913, natural deposits of nitrate fertilizers in Chile were depended on for more than half of the world's supply; but fourteen years later the Chilean contribution had dropped to a mere 16 percent, and 56 percent of all nitrogenous fertilizers was being manufactured out of atmospheric nitrogen. The great fields of cultivated crops covering several billion acres of the earth's surface speak eloquently of man's work in modifying his surroundings. This forced evolution of our environment, with its incalculable influence on the lives of two billion people, owes a great debt to chemistry for discoveries not yet one generation old. When the chemist tells of making something out of thin air he is not speaking of castles in Spain. The very air with which Malthus voiced his pessimistic doctrine has upset his calculations. The great reservoir of the atmosphere, and water power to do the work,

are barely tapped as yet, and billions more of population could eventually feed on the food which chemists can help the farmer raise. But a reasonable policy of common sense in controlling land erosion would be, and is now, imperatively needed.

At first glance one may wonder why nitrogen, which contributes only about three percent of the total weight of the compounds found in the human body, should loom so large on the food horizon. We have already noted that oxygen, carbon and hydrogen comprise 93 percent of the body; but this large figure is apt to convey a wrong idea of the importance of the role left for nitrogen, unless we note also that most of the oxygen and hydrogen exist in the body as plain *water,* which forms more than two-thirds of this flesh-blood-and-bone habitation of ours. To understand how flesh can be firm to the touch, although so largely composed of water, one would need to study its cellular structure. Lettuce, codfish and potatoes, for example, also are firm, yet are mostly water. The percentages of water in these are 94.7, 82.6 and 78.3, respectively. Pound for pound, lettuce contains more water than milk does. The point which concerns us here is that, once we have appropriated enough oxygen and hydrogen to form the water of the body, the amounts of these two elements left to build solids are of the same order of magnitude as that of the nitrogen in the body.

Dismissing water, which becomes a problem only occasionally, in drought-stricken areas, we find that, of all the other materials in the body, combined nitrogen is one of the most plentiful. Lean flesh, when dry, is nearly all *protein* — and nitrogen is the characteristic constituent of all proteins. Several of the *vitamins,* of which so much is heard nowadays, are also nitrogen compounds. Protein molecules are the largest, heaviest and most complicated known. In addition to nitrogen, they all contain carbon, hydro-

gen, oxygen and sulphur. Other elements found in small quantities in certain proteins are phosphorus, iron, zinc, copper, manganese and iodine. But nitrogen, though it constitutes four-fifths of the atmosphere, is the protein element which presents the gravest practical problems.

The air that bathes the leaves of plants is hundreds of times as rich in nitrogen as in carbon dioxide, but plants cannot assimilate the nitrogen by their leaves. A few plants, notably peas, beans, clover, alfalfa and other legumes, are able to assimilate some of the free atmospheric nitrogen in the soil through the agency of bacteria which live in the nodules on their roots. Rotating other crops with these, and preferably plowing the leguminous crop under, is one means of restoring combined nitrogen to the soil. For most plants, nitrates and ammonium compounds found in the soil are the only sources of nitrogen. The cycle is very limited: nitrogen compounds to living plants; plants into animals; excrement, death, decay; nitrogen back to the soil. The net losses of combined nitrogen in this cycle must be made up by fertilization, else mankind will eventually starve. Like Tantalus thirsting in the lake, and hungering while fruit overhead forever evaded his grasp, we should find ourselves helplessly tantalized in our ocean of nitrogen if chemists had not come to our aid. Chemists have learned how to force this unsociable element to combine. They *fix* it to make as good plant food, and cheaper, than the nitrates found where ancient sea fowl deposited guano on the western slope of the Andes. Chile fought a war for the deposit, and took it away from Peru in 1881. For many decades that bed of nitrates, preserved by desert conditions, has helped to feed the soil of the world by the hundreds of thousands of tons, and, more recently, to supply guns with high explosives. Now we draw largely on

the atmosphere for both those purposes. What nations fight for one day, science may give free to the world the next.

Besides its usefulness in increasing the food supply, artificial nitrogen fixation is important for the light it sheds on certain general principles. Strategy based on principles, not blind attack, is the chemist's weapon. The obstacle to be surmounted is the inactivity of nitrogen. Faced by the world's need, the first chemists to attack the problem would have been willing to accept almost any compound of nitrogen. Ammonia, nitric acid, nitric oxide and many other nitrogen compounds were known; but the problem was to *synthesize* a compound, starting with free nitrogen.

The first step is to separate the two atoms which form one molecule of nitrogen, so that they can combine with other atoms. This requires strategy. The nitrogen molecule is very stable, chemically satisfied. Lightning gave one clue to success. By dissociating molecules of nitrogen and oxygen, lightning causes traces of nitrogen oxides to form in the air. Some of the nitrogen atoms encounter oxygen atoms before re-combining, and join with oxygen to form the compound molecules. In the Birkeland-Eyde arc process, air is blown through a powerful *electric discharge*. The nitrogen and oxygen, dissociated by the heat, combine in small quantities to form nitric oxide, from which nitric acid is obtained. This process, originally used in Norway, where electricity is obtained cheaply by water power, has been superseded by the synthetic ammonia process for which Fritz Haber of Germany received the Nobel chemistry prize in 1918. At Niagara Falls and Muscle Shoals the *cyanamide process* is used. Electric furnaces energized by water power make calcium carbide, and the carbide, reacting at high temperatures with atmospheric nitrogen evaporating from liquid air, yields calcium cyanamide. On being

treated with steam or hot water, the cyanamide yields ammonia, from which fertilizers are readily made. But the direct synthetic ammonia of the *Haber process* outweighs all other sources put together. Even the by-product ammonia obtained when coal is distilled to make coke, which for a long time helped Chilean nitrates to carry the burden, plays a relatively subordinate role. The Haber process is the one for us to study.

No matter what process is used in making ammonia, every molecule contains one atom of nitrogen and three of hydrogen. The formula is NH_3. Ammonia is a colorless gas possessing a pungent odor familiar in smelling salts. Breathing very much ammonia, however, is fatal. Gas masks are worn when leaking refrigerating machines filled with ammonia are being inspected. We saw in Chapter 8 that ammonia is useful in refrigeration because of its large latent heat of vaporization and the possibility of liquefying the gas by compression at ordinary temperatures. Ammonia dissolves in extraordinarily large amounts in water, and also reacts with water to form ammonium hydroxide. So-called household ammonia, used to soften water for cleaning purposes, is not ammonia but a solution of ammonium hydroxide in water. Nitrogen, as we have seen, is plentiful, and hydrogen can be readily obtained by any one of a number of methods; but to produce ammonia by the direct union of these two gases one must set the scene with great skill, keeping in mind five general principles or aspects of chemical strategy. Because these five general considerations which apply in the Haber synthetic ammonia process are of wide application elsewhere in chemistry, we stress them in some detail, in logical order.

1. Catalytic Action. The mere mixing of nitrogen and hydrogen in the correct proportions produces so slow a reaction that there is no practical advantage whatever in resorting to this

simple expedient. A *catalyst* is needed. A catalyst is any material which speeds up a chemical reaction without undergoing a permanent chemical change itself. By its mere presence it facilitates the action. Many catalysts have been tried, a number successfully, in the Haber process. An intimate mixture of two finely powdered metals, iron and molybdenum, is one of the best. Apparently these metals form *intermediate compounds*, the iron with hydrogen, the molybdenum with nitrogen; and the intermediate compounds, being very unstable, quickly decompose and liberate atoms (not molecules) of hydrogen and nitrogen. Three *atoms* of hydrogen must come in contact with one *atom* of nitrogen to form a molecule of ammonia. The catalyst acts, so to speak, as a wily marriage broker, bringing the unwilling candidates for this polygamous union together.

The necessity of ensuring a large area of exposure whenever catalysts are used shows that they act as *contact agents*. That intermediate actions are sometimes the secret is suggested by a simple experiment. Small crystals of manganese dioxide, dropped into some barely molten potassium chlorate, cause the chlorate to decompose so rapidly that oxygen comes off with explosive violence. The manganese dioxide used as a catalyst is not consumed; but it goes in as crystals and comes out a powder. Finely divided platinum is the catalyst used in the contact process for large-scale manufacture of sulphuric acid from oxygen and sulphur dioxide. In our own bodies, catalytic actions vital to growth and health are continually in progress. Several of the *vitamins* have already been proved to be catalysts for the oxidation of carbohydrates and fats. A great deal remains to be discovered before catalytic action can be thoroughly understood, but this much is certain: without a catalyst, the Haber synthetic ammonia process, and many another throughout chemistry, simply do not work.

2. *Reversibility of the Reaction.* Another factor which complicates the synthesis of ammonia is the *reversibility* of the reaction. This also is a common phenomenon in chemistry. Even after the catalyst has succeeded in getting some nitrogen and hydrogen to combine, the action can be, in part, undone by the decomposition of the ammonia into the original constituents. In other words, the action can go both backwards and forwards, as the double arrows in the equation suggest:

$$N_2 + 3H_2 \rightleftarrows 2NH_3 + 24{,}000 \text{ calories}$$

Whenever a reversible reaction is allowed to come to equilibrium, the amount of the product (ammonia in this case) is a certain fraction of the total amount of matter contained in the chamber. The value of the fraction depends on conditions. This state of affairs reminds one of the result obtained by shutting up a little water and air in a bottle. An equilibrium is quickly established between evaporation and condensation. At first, water evaporates into the air faster than vapor condenses; but soon, for every molecule of water that escapes as vapor, a molecule of vapor previously formed returns to the liquid. If the bottle is warmed, evaporation is promoted, and a new equilibrium results, giving a denser vapor. If the bottle is cooled, condensation is favored. Similarly, in the synthetic ammonia process. Conditions of *temperature* and *pressure* must be chosen to facilitate the forward action, which produces ammonia.

3. *Choice of Pressures.* Will a low pressure, or high, favor the combination of nitrogen and hydrogen? In deciding this question, we go back to Chapter 7 and remind ourselves of Avogadro's famous hypothesis, now a proved fact. Under similar conditions, *equal volumes of all gases contain equal numbers of molecules.* Our equation shows that *one* molecule of nitrogen combines with

three molecules of hydrogen to form *two* molecules of ammonia gas. Four molecules turn into two molecules. How will this affect the volume? Since equal volumes contain equal numbers of molecules, the more molecules of gas there are, the greater the space required under standard conditions; and the fewer the molecules, the smaller the space. Since the reaction cuts the number of molecules in half, there tends to be a *reduction of volume*. If we do not compress the gas, the molecules will get farther and farther apart as the reaction progresses, and the *pressure* will grow less.

This being so, shall we confine the gases at a high pressure, or low? There is a general principle which decides just such questions as this. It is known as *Le Chatelier's principle,* and applies only to reversible actions in a state of equilibrium. Suppose we increase the pressure. Will that help the action to go forward, or backward? If the change in question tends to *undo* the corresponding change produced by the forward action, *that* action will be furthered. If the applied change tends to *undo* the backward action, *that* action will be favored. This is the essence of Le Chatelier's principle. We have already seen that the forward action (the union of nitrogen and hydrogen) tends to lower the pressure. To undo that effect, we should increase the pressure. In the Haber process, the gases are enclosed in a hollow bomb under a pressure of 150 to 200 atmospheres, or more than a ton to the square inch. In France, modifications using up to seven tons per square inch have been tried. At these enormous pressures, the likelihood that nitrogen and hydrogen atoms will make the necessary contacts is greatly increased. Bombs made of special steel alloys are used. Ordinary iron would not do, for at the pressures used the hydrogen would escape through the solid walls as readily as water through filter paper.

4. *Choice of Temperatures.* In deciding whether or not to heat the nitrogen and hydrogen gases, we apply Le Chatelier's principle again, this time in a form known as *van't Hoff's law.* J. H. van't Hoff was the first Nobel prize-winner in chemistry. His law is merely a special application of Le Chatelier's principle to the temperature problem, so we do not state it again. The equation showed that the union of nitrogen and hydrogen produced so many calories of heat. The heat tends to *raise* the temperature. How is this change to be undone, or opposed? By *lowering* the temperature. Therefore, if we can afford to wait for a final equilibrium to result between the ammonia and the gases that remain uncombined, a *low temperature* will favor a large yield of ammonia, which is what we want. But we cannot afford to wait that long! At low temperatures, the reaction occurs too slowly. Paint manufacturers using the Dutch process to make white lead wait weeks for the lead to be converted, but in the synthetic ammonia industry long waits are not found practicable.

5. *Speed of Reaction.* So we come to the last of the five practical factors in this example of chemical strategy. The higher the temperature, the faster the molecules move, the more frequently they collide, and the more rapidly the union takes place. This factor alone suggests a *high temperature.* But we have just seen that a low temperature promotes a large yield. Here is a fair example of the contradictory requirements which the chemist must often face. Out of a single charge of hydrogen and nitrogen, he can give the world more ammonia by using a low temperature; but he can give us more *per day* by using a higher temperature and letting more of the ingredients pass through the bomb uncombined. So he compromises. Depending chiefly on the catalyst for speed, he heats the gases to about 600 degrees centigrade, only. A ton of nitrogen and hydrogen may yield approxi-

mately two hundred pounds of ammonia on its first trip through the bomb. The remainder must go through again and again.

Once the ammonia has been manufactured, nitrogenous fertilizer is obtained by chemical reaction of the ammonia with gypsum (calcium sulphate) and carbon dioxide. The ammonium sulphate which results is fed directly to the soil. There is now no limit within reason to the amount of combined nitrogen which can be added to the soil. Thus has chemistry warded off the fate which many experts were predicting for mankind only a generation or so ago. Man in the mass will never lack for food unless he simply ignores the marvels of modern chemistry. But may not the triumph over one evil bring another in its train? The same ammonia that feeds the soil, and thence man, also makes possible the high explosives of modern warfare. Haber put his process into effective operation just in time for the World War. As a result, Germany held out for four years instead of one. Now that nitrogen fixation is common in many countries, what of the next war?

Food: a Few Facts in Conclusion

We have now considered, briefly and incompletely, the sources of the four elements — oxygen, hydrogen, carbon, nitrogen — which occur most abundantly in the bodily compounds. In the light of our earlier comparison of human energy with inanimate sources, the rather large space given to the energizing of man may seem out of proportion to his importance as a source of motive power. But machines, though they do most of the work of the world, are made and operated by human beings. We conclude this portion of our study with a few additional facts about food.

In addition to water, the principal classes of foods are carbo-

hydrates, fats, proteins, mineral salts and vitamins. The *carbohydrates and fats* are the oxygen-carbon-hydrogen compounds; they build some tissue, of course, but are primarily sources of energy. *Proteins* give some energy but are most important as tissue builders. *Mineral salts and vitamins* serve to regulate the vital actions of the body.

Among the carbohydrates we have dealt with starch, cellulose, and the sugars glucose, fructose and sucrose. *Cellulose,* the fibrous structure of plants, is not digested. It forms roughage, the necessary bulk to stimulate intestinal action and excretion. *Glucose* and *fructose,* the fruit sugars, enter the blood stream directly by absorption through the intestinal walls and are oxidized by the oxygen which the blood secures through the lungs. These supply energy quickly, for spurts of short duration. *Sucrose,* or cane sugar, requires an intermediate action. The hydrochloric acid of the stomach converts it into glucose and fructose. The same result is accomplished in the intestines by an enzyme called invertase. The net result of this action is to add the two hydrogen atoms and one oxygen atom of a molecule of water to the sucrose molecule, which then splits evenly into glucose and fructose, as shown by the equation:

$$C_{12}H_{22}O_{11} + H_2O \rightarrow C_6H_{12}O_6 + C_6H_{12}O_6$$

Starch, also, is converted into glucose; this change is produced by enzymes of the saliva and by intestinal juices. Any excess of carbohydrates above immediate energy requirements is at first stored in the liver and muscles as animal starch (glycogen), where it acts as a reserve source of energy; but a continuance of the excess results in the formation of *fat.*

Although more than half of the energy required to maintain the bodily temperature and to do muscular work normally comes

from the oxidation of the glucose in the blood, fats are a more enduring source of energy, and far richer. They yield an average of about 4,000,000 calories per pound, the carbohydrates about 1,800,000. *Proteins,* though primarily body builders, yield about as much heat per pound as do the carbohydrates. Thus a pound of butter is the energy-equivalent of somewhat more than two pounds of sugar or two pounds of lean meat. The average man needs from a sixth to a quarter of a pound of protein food daily, and enough fats and carbohydrates to bring the total energy up to about 3,300,000 calories a day. Foods rich in *protein* are lean meat, fish, poultry, eggs, oatmeal, peanuts, beans. Foods rich in *fat* are bacon, butter, eggs, ham, chicken, peanuts, salmon. Foods rich in *carbohydrates* are apples, bananas, beans, bread, corn, oatmeal, oranges, peanuts, peas, potatoes, prunes, rice. Milk is an all-round food, furnishing proteins, fats and carbohydrates in nearly equal quantities, and supplying *calcium* and *phosphorus,* which are essential to health and strength of bodily structure. Eggs and meats help to supply the needed phosphorus. The leaf-parts of leafy vegetables are rich in both calcium and *vitamins.*

The importance of vitamins has been thoroughly publicized. These organic food substances are required in daily quantities so small, ranging from a few hundredths of a milligram of certain vitamins, to a few milligrams of others, that it might have been difficult for the public to believe what biological chemists told them about vitamins if history had not presented the object lesson of microbes, which were rejected by the early scoffers on the theory that they were much too small to bring so large and impressive a being as man to his bed and grave. The body does not manufacture vitamins, as it does the *hormones* which are secreted by the ductless glands; but one of these two classes of chemical compounds brings to mind the other, for together they seem to be the

chief *regulators* of vital actions which control health, growth and, to a certain extent, character as well. Needless to say, chemistry is intimately concerned with both vitamins and hormones. Adrenalin, the hormone secreted by the suprarenal glands, has been synthesized commercially and is administered by medical men when needed. Insulin, the hormone of the pancreas, has been extracted in a pure state by chemists and is widely used in the treatment of diabetes. Thyroxine, the active agent of the thyroid gland, has been prepared artificially from coal-tar products. A female sex hormone, theelin ($C_{18}H_{22}O_2$), has also been synthesized. Reverting to the vitamins, we should note that they were originally discovered by inference from the results of feeding experiments, not by chemical analysis; but already several of the vitamins have been isolated chemically and their formulae discovered, so that the day is possibly not far off when they will be prepared and administered with the accuracy which characterizes other branches of chemistry.

Knowledge of the different kinds of vitamins, though far from complete, has already brought great benefit to humanity. A number of diseases not understood before the discovery of vitamins can now be prevented. *Fat-soluble vitamin A* is the growth-producing vitamin, and also helps to prevent a disease which often causes blindness. It is plentiful in whole milk, egg yolks, cod-liver oil, butter, spinach, lettuce, celery, beet-tops, liver, kidney, sweetbreads. It survives moderate cooking reasonably well, but is oxidized, therefore destroyed, by prolonged heating in contact with air. *Water-soluble vitamin B* is the one needed to prevent beri-beri and certain nervous disorders. It is found in fruits, green leaves, and in the hulls of cereal grains. Concentration on a diet of polished grain has caused beri-beri; eating the hulls has cured it. *Water-soluble vitamin C* is abundant in citrus fruit, tomatoes, and

in fresh fruits and vegetables generally. This is the anti-scorbutic, or scurvy-preventing, vitamin. Vitamin C is best preserved in slightly acid solutions. *Fat-soluble vitamin D,* the antirachitic vitamin, is apparently produced by the action of ultra-violet light. Exposure of rickets victims to sunlight (which is moderately rich in ultra-violet) has worked remarkable cures; the same result has been accomplished by exposing the food to ultra-violet. If sunlight is depended on, one should get it outdoors, or through special glasses which are permanently transparent to the ultra-violet. Ordinary window glass absorbs most of the ultra-violet, and some of the commercial substitutes may lose their transparency to the ultra-violet. Vitamin D seems to control the concentration of phosphorus and calcium in the blood, hence indirectly to influence the nervous tissue, which is rich in phosphorus, and the bones, which contain much calcium.

Some, possibly all, of the vitamins act as catalytic agents, regulating the speed of certain actions, and doubtless making possible others which, in the absence of vitamins, would not occur. The list given is not complete. Vitamin E influences fertility in the female, hence reproduction. A vitamin called G has been reported. The vitamins contribute a negligible amount of energy, but they enable the body to convert food elements into sound growth and capacity for work. Present knowledge of food chemistry can make possible a far healthier generation, no doubt, than any yet brought to manhood. With these few remarks, we leave the interested reader to refer to the excellent books on biological chemistry which are available, while we pass on to other agencies for doing the world's work.

Fuel Resources

Our times are often called the electric age; but we have come far enough in our study to realize that the work of the world is done largely at the expense of chemical energy. We have seen that man, one of the lesser of civilization's agencies for doing physical work, is energized by sunlight relayed to him through the marvelous rearrangements of atoms in growing plants. The table of other sources of energy given at the opening of this chapter showed that chemical agencies predominate. Combustion, like digestion and oxidation in the body, is a rearrangement of atoms, a chemical action. Most of man's work is done, directly or indirectly, at the expense of burning fuels. The steadily increasing electrification of the world, with the great gain of convenience, health, cleanliness and beauty that results, may seem to belie this statement; but we must bear in mind that only a fraction of the electric energy of the world is at present generated directly from the kinetic energy of falling water, a non-chemical source. In the period from 1920 to 1935, the *total* amount of electric energy generated in the United States by both fuel and water power increased very nearly as much as did the water-power electricity alone — 128 percent of increase against 147. Hence the use of fuels to generate electricity increased nearly as rapidly as the use of water power. In 1935, only 40 percent of all the electricity generated in this country came from water power. The remainder, more than half, was obtained at the expense of fuels. But even if all the electric energy now being used in the United States were developed by water power, it would still need to be multiplied fifty-fold to equal the energy gained from chemical sources.

This means that civilization is living on its capital, not its income. Even in agriculture, which could feed the world on the

interest of our capital resources in the soil if erosion were adequately controlled and fertilizers used in sufficient abundance to maintain the soil's fertility, we draw heavily upon natural capital for our daily food. Coal and petroleum resources are consumed without any replacement that we know of. Coal is the fossilized vegetation of by-gone ages. Once used, it cannot be replaced until geological ages have come and gone. A short lag, or delay, in the utilization of the radiant energy of the sun is a great convenience, as attested by our use of growing crops; but the almost unimaginably long lag in applying that same source of energy through the medium of coal is a convenience only for the race that happens to inhabit the planet at the right period of geological history. Peat, the forerunner of coal, is now forming in the great Okefenokee swamp of Georgia and the Dismal swamp of South Carolina and Virginia; but the matted vegetation now decaying and accumulating there in layer-on-layer compressed formation will not be coal until, if history repeats, hundreds of civilizations have waxed and waned. Petroleum, too, is a fossil fuel, a mixture of *hydrocarbons* whose molecules are composed of hydrogen and carbon atoms which once, in all probability, helped to form the bodies of marine plants and animals. No replacement of petroleum is known to be in progress in nature. The gasoline engines purring over our roads or roaring through the air, the Diesel engines burning crude oil to drive ships over the water highways of the world — these, too, are undoing at a tremendous rate the priceless chemical changes which occurred in the age of dinosaurs, or earlier. If we are to be prudent trustees, not reckless heirs squandering the estate with thoughtless prodigality, civilization should control erosion, fertilize the soil, replace forests, and, as rapidly as possible, extend the utilization of current sources of energy income, such as water, wind, tide, direct sun-power, and liquid

fuels made out of growing crops. The scientific knowledge needed to direct sound conservation programs is available in ample measure.

Alarmists have often painted exaggerated pictures. In 1922 a group of geologists representing both private and federal interests estimated that nearly half of the petroleum resources of the United States had been used in the short period since Col. E. L. Drake drilled the first oil well in 1859, and that the reserve was being used at a rate which would exhaust it in twenty years. Yet three years later, as a result partly of the discovery of new fields, partly of improved chemistry of refining, the American Petroleum Institute concluded that this country would continue to possess a sufficient supply of oil beyond the time when the apparent emergency would be removed by the economical manufacture of substitutes, the harnessing of current sources of energy and the more efficient use of the sources stored underground by nature. At the present rate of use, however, the world's petroleum supply seems to be a matter of decades, not centuries. Tourists know the high cost of gasoline abroad. In Paris, the omnibuses have already consumed great quantities of a fuel half alcohol, half gasoline. In the first thirty-five years of this century, the world's annual consumption of petroleum increased almost exactly eleven-fold; and in the last year of that period, 1935, the United States contributed 60 percent of the world's production. The United States possesses slightly more than half of the world's known coal deposits — enough to keep us running, at the present rate of consumption, for several thousand years. In England and Germany, the national coal reserves seem to be good for a few hundred years. Abroad, the search for substitute fuels is pressed more urgently than here. This country's good fortune in resources can easily lead to a false sense of security. A world running painfully short of fuel would

not sit idly by while one nation enjoyed abundance. If we give science its head, the interests of those to come can be safeguarded without sacrifice of the abundance which we have come to expect at the hands of science.

Utilization of Fuel to Do Work

Chemical action locked energy in the molecules of fuels; another chemical action sets it free. Combustion, a rapid oxidation, has been mentioned several times in our pages; and in Chapter 8 a good deal of space was given to the physical principles which underlie the actions of heat engines. For our present purposes, only a few details need be added.

The fuel is heated to the kindling temperature to start the action. It then unites with oxygen from the air, producing heat and chemical compounds. The amount of heat and the nature of the products of the reaction depend on the kind of fuel used and on the degree of completeness of the burning. Once the heat is obtained, it can be used to vaporize water and expand the vapor, as in steam engines. The pressure of the expanding steam may push the piston of a reciprocating engine, giving the back-and-forth motion of the driving shaft of the usual locomotive; or it may drive turbine wheels in a continuous windmill fashion by pressing against multitudes of vanes. In many ocean liners, high-speed turbines are used to drive electric dynamos, which in turn energize the electric motors that actually spin the propellers. In internal combustion engines, the hot expanding gas is produced by combustion directly within the cylinders, not in a furnace under a boiler, as in a steam engine. The gasoline engines of automobiles, and the Diesel engines now being installed in rapidly increasing numbers in industry and heavy transportation, are both of the

internal combustion type. Automobile engines utilize the high pressures produced by combustion of gasoline vapor mixed with air; the Diesel engine commonly uses crude oil sprayed into hot compressed air in the cylinder. The Diesel engine requires no electric spark plugs to start the combustion: the air in the cylinder is heated so hot by a preliminary compression stroke that the crude oil ignites spontaneously when sprayed into it. The reader inclined toward engineering will look up the details of carburetors, valves, timing and the function of every stroke in a complete cycle of the engine; but here we are chiefly concerned with the nature of the chemical actions and the amount of work that can be done at the expense of a pound of fuel.

Coal is a complex mixture of compounds. Carbon is the most plentiful element combined in coal, the percentage by weight ranging from 65 to 81. From two to nine percent may be water. The remainder contains mineral matter and oxygen, nitrogen, hydrogen and sulphur in combined form. The richness in carbon, and the poverty in oxygen, account largely for coal's excellent heat-producing capacity. The carbon can take up large quantities of oxygen in burning. The sub-coals, lignite and peat, are richer in water than coal is, and proportionately poorer in carbon, hence have low fuel values. These crumbly sub-coals are widely used in briquet form in certain countries whose coal supplies are meager.

The carbon in coal is oxidized during combustion, forming carbon dioxide if sufficient air is supplied. The complete combustion of a pound of pure carbon yields 3,670,000 calories; good bituminous (soft) coal about the same; and anthracite, or hard coal, a few percent more. The fact that good coal gives about as much heat as pure carbon, although twenty percent or more of the coal is not carbon, shows that other elements combined in coal contribute to its fuel value.

The by-products which can be obtained from coal are of great industrial importance. The destructive distillation of a ton of bituminous coal by heating in the absence of air yields 1200 to 1500 pounds of coke; 10,000 to 12,000 cubic feet of fuel gas; 11 to 13 gallons of a tar which is one of the most valuable of the raw materials used in the dye, drug, and explosives industries; several gallons of oil; and enough ammonia to make about 24 pounds of ammonium sulphate fertilizer.

The fact that bituminous coal is distilled by the millions of tons in the United States every year for the sake of the by-products shows the wastefulness of shipping the coal around the country to be burned in the ordinary manner. The fuel gas can be piped to homes and factories; and the coke is not only a superior fuel for household furnaces, but is used in the United States in quantities of the order of 50,000,000 tons annually to supply the carbon monoxide needed to reduce iron ores to metallic iron in blast furnaces. Naturally, there are good economic reasons why great changes cannot be made suddenly; but it seems that eventually very little solid fuel, if any, will be shipped far from the mines. Gas and electricity for homes and factories, with a steadily increasing conversion of fuel energy into electricity for convenience and cleanliness; and liquid fuels for transportation of all kinds — these seem to be the trends.

The refining of petroleum to produce gasoline involves two interesting processes, *fractional distillation* and *cracking*. The oil as it comes from the ground is, like coal, a complex mixture. The more important products recovered from it are petroleum ether, gasoline, naphtha, benzine, kerosene, lubricating oils, vaseline, and a residue of paraffin, asphalt, or coke, depending on the source of the oil. The original mixture contains a series of compounds of carbon and hydrogen called hydrocarbons. These have different boiling points, hence can be partially separated from one another

by fractional distillation. The liquids which boil at the lowest temperatures evaporate first. The vapors are caught, condensed by cooling, and kept separate. By a similar process one can recover alcohol which has been dissolved in water or formed by natural actions in a fermenting mash.

Gasoline, for example, is composed largely of hexane (C_6H_{14}) and heptane (C_7H_{16}). Kerosene contains the series running from decane ($C_{10}H_{22}$) to hexadecane ($C_{16}H_{34}$). The possibilities of the hydrocarbons may be judged by the number of atoms in a molecule of one of the higher members of the series, $C_{35}H_{72}$. Remembering formulae is not recommended unless for a special purpose. What interests us here is the fact that the boiling points of the liquids in this regular series of compounds rise steadily as the number of atoms in the molecule increases. The liquids in gasoline boil at temperatures between 70 and 90 degrees centigrade; those in kerosene from 150 to 300. The refiner takes advantage of these differences to separate the desired products.

The discovery that the hydrocarbon molecules which contained too many atoms to be included in gasoline could be broken up by means of high temperatures and pressures, in the absence of air, has led to a far greater efficiency in our use of petroleum. This process, called *cracking,* has nearly doubled the amount of gasoline obtained from a barrel of crude petroleum. The sixty million tons of petroleum gasoline produced in this country in 1935 were obtained from approximately half as much petroleum as would have been needed to produce the same amount in 1913, the year the cracking process was discovered. This one triumph of applied chemistry nearly doubled the value of the oil resources of the world. There is an item to be placed alongside the fixation of nitrogen, which made four-fifths of the atmosphere potentially useful to man.

Gasoline is a more concentrated fuel than coal. Its heat of combustion is about half again as great as coal's. When the mixture of hydrocarbons which compose gasoline is mixed with air in the automobile cylinder and ignited by the electric spark, burning takes place, producing carbon dioxide and water. The reactions of the principal ingredients (with one question mark for the reader's ingenuity) are:

$$2C_6H_{14} + (?)O_2 \rightarrow 12CO_2 + 14H_2O$$
$$C_7H_{16} + 11O_2 \rightarrow 7CO_2 + 8H_2O$$

How many of the two-atomed oxygen molecules are needed to balance the first equation? And how would you balance the corresponding equation for the combustion of one of the components of kerosene, say $C_{10}H_{22}$?

The reactions are interesting for several reasons. This is a gasoline engine, but we have some *steam* blown out through the exhaust! Try holding a cold metal plate against the exhaust and note the condensation of water. The water formed by the reaction is of course vaporized. It is the carbon dioxide and the water vapor, together with the non-oxygen part of the air, heated to a great pressure by the combustion, which push the pistons that propel the wheels. And we note that the reaction is clean: there is no solid residue if the gasoline contains no foreign matter. In practice, some deadly carbon monoxide, the result of incomplete combustion, is always present in the exhaust.

The efficiency of the internal combustion engine increases with the extent to which the gases or vapors are compressed before combustion begins. At too high a compression, the smooth wave of combustion spreading through the gases turns into a rapid wave of explosion, which causes knocking. Higher compression without knocking, hence greater efficiency, can be obtained by adding

certain other compounds to the gasoline, the best known of which is lead tetraethyl $(C_2H_5)_4Pb$. Pb is the chemical symbol for an atom of lead. One of the reasons for the relatively high efficiency of the Diesel engine is that it permits of very high pressures ranging up to 500 pounds per square inch.

All heat engines, however, seem very inefficient when compared with an electric motor or transformer. A locomotive steam engine may convert into mechanical work as much as 10 percent of the heat energy supplied to the boiler; a steam turbine 25 percent, an automobile engine 25, the best Diesel engines 34 percent. By far the greater portion of the energy is wasted. The reason for this wastefulness is not imperfection of design; the figures given are for good heat engines. By re-reading the discussion of the perfect heat engine in Chapter 8, one can find why all heat engines are necessarily inefficient. The real difficulty is that the absolute zero of temperature is so far below the temperature of our surroundings. In addition to all other losses, the expanding gases which do the work are bound to carry out with them a large fraction of the heat produced by combustion. Only if they could keep on expanding and pushing the piston until they had cooled themselves to absolute zero, could an efficiency of 100 percent be attained by a heat engine that was perfectly constructed and operated.

Electricity Compared with Other Sources of Energy

Since so great a waste necessarily attends the conversion of the chemical energy of fuels into the useful kinetic energy of moving machinery and vehicles, why then, one may ask, do we bother with heat engines at all? Why do we not use electric apparatus exclusively — apparatus which commonly reaches the high levels of 90 to 98 percent of efficiency?

Physics and chemistry can answer this question only in part. A full discussion would lead us into economics, social behavior and governmental policy — fields in which experts disagree. No doubt human inertia, reluctance to change, has been one factor in retarding the electrification of the world. It is only a century since Michael Faraday discovered the principle of electromagnetic induction, which is applied to generate all the electricity used for power purposes in the world; and more than half of those hundred-odd years passed by before industrial and household applications of electricity began to be of appreciable practical importance. But a glance at the table given at the opening of this chapter shows that the youthfulness of practical electricity cannot be the whole answer. The gasoline industry, too, is young; yet the table shows that in 1935 petroleum gasoline was running far ahead of water-power electricity in contributing to the country's supply of energy. The ratio was 630 to 34. If we take into account all the electricity generated by both water-power and fuel in the United States, we find that the energy value of the petroleum gasoline produced in 1935 was more than seven times that of electricity — and coal towered above both in its historic role of energy colossus of the modern age. Making the rounds of homes, theatres, shops, office buildings and streets in a modern city, noting the electric refrigerators and ranges, electric fans, electric elevators, electric air-conditioning, electric entertainment, the brilliance of incandescent lights and neon advertising signs, one might conclude that electricity is already the leader; but figures belie that impression. Electricity, however, is gradually gaining. If we prepared an energy table like the one referred to above, but using the figures for 1920, we should find that the relative importance of water-power electricity, compared with the total energy given by the table, was about two and a half times as great in 1935 as in the earlier year.

The tourist thrilled by the majestic spectacle of Niagara falls feels no similar emotion when obtaining a tankful of gasoline for the car that brought him there; yet to match the energy of a single gallon of gasoline, thirty-two tons of water must hurtle down the 167 feet from top to bottom of Niagara. The extreme compactness with which energy is concentrated in good fuels, its ready portability, the ease of storing it for use as needed, all make for convenience in many applications.

In other applications, the initial cost of development retards the electrification of the country. At natural falls, expensive installations capable of handling enormous quantities of moving water are required to generate electric energy on an industrial scale; and where natural falls are lacking, dams costing millions of dollars must be built. At the junction of Cove Creek and the River Clinch, where the Tennessee Valley Authority is at work, Norris dam is designed to tower more than half again as high as Niagara falls. Steel buckets pouring thirteen tons of concrete every three minutes worked for two years to build it. The dam is expected to store fifty million billion tons of water, the year's rainfall gathered from several thousand square miles, in a lake covering eighty square miles. Even if all that water fell the full height of 266 feet, its kinetic energy at the bottom would be equal to no more than about two and a half percent of the energy produced by burning the country's 1935 coal supply. But anywhere in the country, whatever fraction of water's energy of motion is converted into electric energy, is so much energy gained from the current income of natural resources, not a drain on irreplaceable natural capital. The use of water power is one means of conserving natural resources.

Since this chapter deals with the world's work, energy is the key word. The progressive manufacturer who uses coal buys it, not

by the ton, but by so many units of energy. Users consider cost in choosing sources of energy. This is one reason why electricity at present plays a relatively minor role in the scale of energy. The average householder in middle and northern latitudes thinks nothing of burning a ton of coal in a week of cold weather, but if he received a weekly bill for eight thousand two hundred kilowatt-hours of electric energy he would be painfully shocked if he had not steeled himself in advance. Yet a ton of coal gives the same amount of energy as that seemingly large quantity of electric energy.

In the use of electricity, economic conditions have led us to regard as large, quantities of energy which would be considered insignificant if coal or gasoline were the source. If the energy of coal were expressed in kilowatt-hours, instead of calories, the discrepancy would be apparent at a glance. At eleven dollars per ton of coal, energy costs only about one-eighth of a cent per kilowatt-hour. However, the greater efficiency with which electric energy can be used should be taken into account. In the usual coal furnace, much of the heat goes up the chimney. Since electric heating requires no draft of air, waste can be reduced to a minimum. How small our ideas are in the field of electricity may be judged by the thicknesses of the wires with which the average private home is wired. We saw above that 8200 kilowatt-hours would be needed to match the energy of one ton of coal. To yield that many kilowatt-hours in one week, at the usual household voltage of 110 volts, a current of 444 amperes would need to flow continuously, day and night, and the copper bringing that current to the furnace should be, not a wire, but a solid copper rod at least half an inch thick, to avoid overheating. Actually, many homes are wired with copper not much thicker than the lead of a pencil. Ways of transmitting far larger amounts of power with-

out using wires of excessive thickness will be considered a few pages farther on.

These are some of the reasons why the use of electricity has been so largely restricted to applications in which cleanliness, convenience, ease of control, or special adaptability, as in lighting and communication, offset the high cost per unit of energy. More than half of the electric energy of the country is still generated by means of fuel power, and therefore, although capable of being used with high efficiency, must bear the cost of the great and unavoidable waste inherent in the heat engines that turned the dynamos. This consideration does not apply to water-power electricity, but there the cost is affected by the expense of the generating facilities, including the dam if one is required. Another complication is the lack of any economical means of storing electric energy. It must be used as generated; whereas coal or gasoline is readily stored. Storage batteries are used by the millions in automobiles for starting and lighting, but are not economical sources of power. Storage batteries do not store electricity. The coated lead plates undergo a chemical action when electricity is forced through the battery in one direction, and they then can produce limited currents in the opposite direction by the reversal of the original chemical change. As with other commodities, quantity production of energy tends to lower the costs.

People a generation hence may smile when they read our present ideas of what constitutes a large quantity of electric energy. There is no scientific reason why a cold house could not be heated *almost* as suddenly as a dark one is lighted, by the throw of a switch. Potential sources of energy, and the scientific knowledge to deal with them, are ahead of our applications. The determining factor is chiefly what seems desirable and economically feasible in a given generation.

The Generation of Electric Currents

All matter contains electricity. We saw that in Chapter 9. No one will be surprised, then, to learn that currents of electricity can be produced by many means. Any form of energy can be converted into the energy of moving electrons. Light, heat, chemical energy and the kinetic energy of motion afford the principal means of generating electric currents. All that is necessary is to separate the positive and negative electricity which are found in (or which compose) all matter, and to continue the separation against the natural tendency of the positive and negative electricity to settle into a state of equilibrium under each other's attractive force and thus neutralize the migration. The free electrons of metals move most readily, hence the currents used in practical work consist of streams of free electrons moving through metallic conductors.

If the current is to be *direct,* the electrons must keep on flowing in one direction. We learned in Chapter 9 how many electrons must pass a given point of a wire every second in order to constitute a current, or rate of flow, of one *ampere*. In electricity, a quantity called difference of potential corresponds to the difference of pressure at the two ends of a water pipe through which a current of water is flowing. Difference of pressure makes the water flow; difference of potential makes the electrons move. Difference of potential is, then, the electromotive force. It is measured in *volts,* hence is often referred to as voltage. Dry cells give about one and a half volts each; private farm-lighting plants usually furnish 32 volts; the power circuits in home 110 or 220 volts; the wires in the city streets something over two thousand; the electric chair from two thousand to five thousand volts; long-distance transmission lines from sixty thousand to nearly three hundred thousand; Van der Graaff's high-voltage generator up to ten million volts.

This latter voltage will cause the electrons to jump clear of the wires and produce an awe-inspiring stroke of artificial lightning longer than the average living room. Electricians through long familiarity sometimes grow contemptuous of the shocking ability

FIGURE 41. Student engineers of sixteen colleges on one of the 82,500 kilovolt-ampere waterwheel generators for Boulder Dam. (Courtesy General Electric Company.)

of ordinary voltages, and test for live wires by submitting themselves to minor shocks; but readers unfamiliar with electricity are warned against taking chances. The household voltage of 110 has killed so many hundreds of people that most localities have ordinances against placing light-sockets where they can be reached from a bathtub. The water completes the circuit between bare

flesh and the metal pipes that lead to ground; and since one side of a household lighting circuit is always connected to ground, a grounded person who accidentally touches the other, or ungrounded, side of the circuit completes a path through which the electricity can flow. Painful shocks can be suffered through tampering with the connections of a modern radio set, where upwards of six hundred volts are commonly used. Dry cells and storage batteries are perfectly harmless singly; but if many of them are connected in series, positive of one to the negative of the other, the extreme terminals may provide voltages capable of producing shocks. In general, the safe rule is to regard electricity with great respect. Cut and fit methods have no place in dealing with this invisible servant of man. With light and a camera lens, for example, one can safely find the proper focusing distance by trial and error; but whenever an electric switch is closed to complete the circuit and let the electrons flow, whatever was going to happen has already happened before the switch can be opened. It may not be true that electricity acts faster than anybody can think, for nobody knows what thinking is; but electricity certainly acts faster than anybody can give any evidence of thinking. Hence the scientific method alone, the calculating in advance of the correct conditions, can give satisfactory results in dealing with electricity. This extra rule of the game is doubtless one reason why electricity has fascinated so many thousands of amateur experimenters.

Electric currents used for power purposes are almost always *alternating,* not direct. The electrons oscillate back and forth through very small distances in the wires. The usual frequency in home lighting is sixty cycles per second. No difficulty is encountered in making currents alternate; the difficulty is rather the opposite. Alternating currents are automatically produced by the

natural action of a dynamo generator. Dynamos which give direct currents are usually alternating current machines with one extra device, a commutator of some sort, added. This automatically reverses the connections every time the current reverses in the generating coils and thus keeps it flowing in the same direction in the external circuit. The two reversals nullify each other. In charging batteries and supplying power for radio sets, the alternating character of the current is an inconvenience, requiring the use of *rectifiers* to give direct current; but in the larger problem of transmission of power the currents, for reasons that we shall soon consider, should be alternating.

The question naturally arises, what does an alternating current of one ampere mean if the current is continually changing many times a second? The practice is to consider an alternating current to be one ampere when it causes the same heating effect in a lamp, stove, or other heating appliance as would be produced by a direct current of one ampere. By this definition, the *instantaneous* values of what is called one ampere of alternating current range from 1.41 amperes in one direction to 1.41 amperes in the opposite, and pass through the zero-value 120 times a second if there are sixty complete cycles per second.

Dry cells and storage batteries generate direct currents by means of chemical action. The essential difference between the two types of cells is that in one the chemical action is not readily reversed by forcing electricity through it in the backward direction, in the other it is. The latter can therefore be re-charged. Two rods or plates of any two different metals, immersed in a solution of any acid or chemical salt, generate electromotive forces by chemical action. Some combinations, of course, are more effective than others. Light produces direct electric currents by photoelectric action. Some applications of photoelectric cells will be considered

in our chapter on communication. Direct currents are also obtained by the action of heat on thermocouples. A thermocouple is a circuit formed of wires of two different metals joined together. When one junction is made warmer than the other, an electric current flows. This method is not applied for power purposes (except in special spectacular demonstrations) but is very useful indeed in the measurement and automatic control of temperature. Electric thermometers of the thermocouple type range from the supersensitive instruments capable of measuring the temperatures of stars at distances of many light-years, to the more rugged instruments which take up the work of measuring high or low temperatures where mercury-in-glass thermometers necessarily leave off. There is also frictional electricity, readily demonstrated by combing the hair with a rubber comb on a dry day, or by rubbing a hard rubber rod with flannel and picking up bits of paper with the electrified rod. Leather belts running over pulleys in factories are sometimes provided with pointed metal combs near them to dissipate the frictional electricity and thus prevent sparks which might cause explosions of combustible gases or mere dust. One often sees a gasoline truck dragging a short length of chain behind it for the same purpose.

But *electromagnetic induction* is the only practical method yet discovered for generating electric power in industrial quantities at the expense of other forms of energy. Storage batteries, it is true, are sources of appreciable power in automobiles, private lighting plants, and emergency systems for ships, hospitals, or other public institutions; but these may be looked on as secondary sources which depend primarily on being charged with electricity generated by electromagnetic induction.

Commercial dynamos all operate by induction. The simplest experimental generator of the dynamo type consists of a closed coil

of wire and a U-shaped iron magnet. When the coil is rotated between the poles of the magnet, an electric current is induced in the coil. The more rapidly the coil is rotated, and the greater the number of turns of wire it possesses, the greater the electromotive force, or voltage, that is generated. By increasing the strength of the magnet, the induced voltage can be increased still further. Since a given face of the coil is presented alternately to the north and to the south pole of the magnet, continuous rotation of the coil is bound to generate an alternating current unless some compensating reversal is made in step with the rotation of the coil. The compensating reversal, if desired, may be produced by reversing either the connections of the coil or the polarity of the magnet between whose poles the coil is rotating. That a magnet *has* polarity can be discovered by observing a mariner's magnetic compass, or by hanging up a bar magnet by a slender thread: it sets itself approximately north and south due to the earth's magnetism. A strong magnet can be made by wrapping a coil of wire around iron and passing a current through the coil. The iron becomes a magnet, and its polarity depends on the direction in which the current flows. Such a magnet is called an electromagnet. Except in measuring instruments, commercial electricity relies only very slightly on the permanent magnetization of iron. Electromagnets of as great strength as desired can readily be made. In some dynamos, the residual magnetism retained by the iron after one period of operation is utilized to start the inductive action the next time the dynamo is set to rotating, and the currents thus produced are fed through coils wound around the iron to increase the magnetization and thus build up the inductive action.

Modern dynamo generators are rather complicated, possessing coils wound in several sections, and more than one pair of magnet

poles. The exact laws governing the design and functioning of such equipment are well known; but for our present purposes two basic principles, only, need be remembered. First, electric currents produce magnetic forces. Second, relative motion between a coil of wire and a magnet, or any equivalent of such a motion, induces an electromotive force.

To understand the expression, *any equivalent of such a motion,* consider two entirely separate coils of wire wrapped around the same rod of iron, or one inside the other. If an *alternating* current is passed through one coil, an alternating current will be induced in the other. Here there is no actual motion of one coil with respect to the other; but the alternating current forced through the first (primary) coil causes that coil to become a magnet of continually changing strength, and the effect on the other coil, the secondary, is the same as if a magnet were successively thrust inside it, removed, reversed, inserted again, and so on indefinitely. This is the principle of the *transformers* that one sees mounted on poles on city streets. Alternating current of fairly high voltage is fed through one coil, and alternating current of a less dangerous voltage is induced in the other for a house or group of houses. Any voltage within reason, high or low, can be obtained by winding the correct numbers of turns of wire in the coils. For example, if the secondary coil possesses only one-hundredth as many turns as the primary coil, the secondary voltage will be only one-hundredth as great as that supplied to the primary. Transformers are used either to step-up or step-down voltages as desired, but are not primary sources of energy. They merely change the voltage. The primary source of electric energy is the dynamo, which draws its energy from the machine that turns the coil. Turbine wheels driven either by steam or by water power are the usual agencies for turning dynamos. Wind power has also been utilized on a

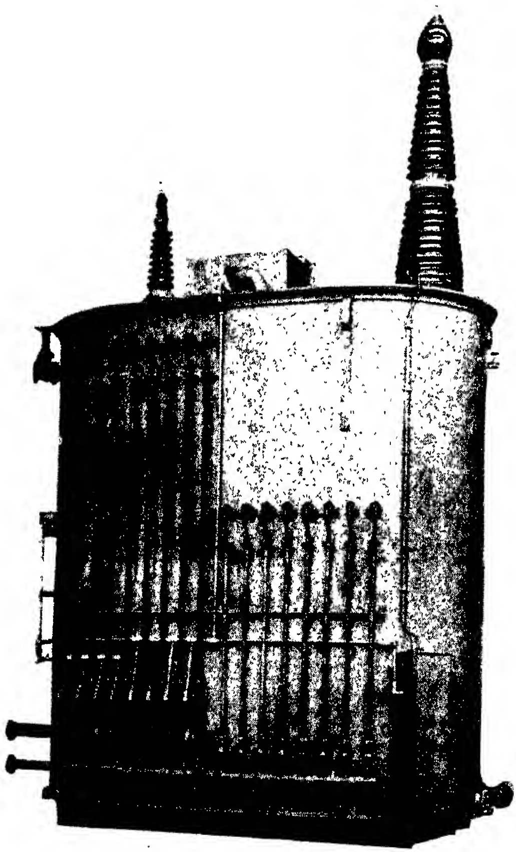


FIGURE 42. 55,000 kilovolt-ampere transformer built for U. S. Bureau of Reclamation, Boulder City, Nevada. It steps the voltage down from 287,500 to 16,320 volts. The high-tension insulators at the top are grooved to oblige the electricity to traverse a long distance if any is to creep over the surface. The over-all height is about 30 feet. (Courtesy General Electric Company.)

small scale: windmills drive dynamos. Anything that *moves* can generate electricity if we set the scene properly.

Transmission of Electric Energy

The transportation of large quantities of electric energy presents interesting problems. Traveling through the country one observes the high-tension power lines strung on lofty steel towers, the wires far apart and protected from contact with the supporting structures by massive porcelain insulators whose sides have been moulded into a series of curves to oblige the electricity to traverse a long distance if any is to creep away over the surface. How different those mountings from the ones used by the electrician in wiring our homes, and how much more expensive! Why is electricity transmitted at voltages so high that such precautions are needed?

The quickest way to reach an answer is to consider a representative problem. Suppose a small community contains a thousand homes, each of which is burning four sixty-watt lamps at the time we study the situation. That would be 240,000 watts. Let enough radios, electric refrigerators, motors, waffle irons, street lights and advertising signs be operating to bring the total amount of electric power to 550,000 watts. Energy must be transported at this rate from dynamos which are being driven, say, by water falling over a dam sixty miles away. Shall we seek to have that power delivered to the outskirts of the village at 110 volts, the low voltage we use in our homes; or shall we agree to receive it at the dangerously high voltage of, say, sixty-six thousand volts, and then by use of transformers step it down before distributing it around the town?

Suppose the city fathers decide that they will not have anything to do with voltages so dangerous to life. They insist on receiving the power at 110 volts. Very well. A given amount of power

can be supplied either by a large current at a low voltage, or a small current at a high voltage. How many amperes must flow in the transmission line to supply the required 550,000 watts at a delivered voltage of 110? The law that answers this question is Joule's law: the power P in watts equals the current I in amperes multiplied by the electromotive force E in volts; or $P = IE$. *Power equals current times voltage.* Hence 550,000 equals 110 times the current. The current must be 5000 amperes; for 5000 times 110 equals 550,000. (This answer would be exact if direct current were used, but needs a small correction by what is known as the power factor for the alternating currents actually employed.)

What sort of conveyance will bring those five thousand amperes of current to town? Copper wires. How thick must the wires be? Let us dodge that question for a moment, and suppose that the transmission line consists of solid copper wires (really rods) of the size known to electricians as 0000. These are nearly half an inch thick. Since the powerhouse is sixty miles away, the total length of wire is 120 miles. By referring to tables we find that the wire possesses an electric *resistance* of 28.6 *ohms*. Copper is a good conductor, but of course it offers some resistance to the flow of electrons through it. In some places resistance is desired, in others it is purposely kept small. For example, the same current flows through both the lamp cord and the lamp filament; but the filament, not the connecting wires, is the part that becomes white-hot, since it has purposely been made of a thin wire of a metal which offers high resistance.

To find the effect of the resistance of the transmission line we need another law, Ohm's law. This tells us that the voltage equals the resistance times the current, or $E = RI$. If for R we use the resistance of the transmission line, then the E that we calculate is the voltage-drop, or loss of voltage, in the line. This

FIGURE 43. Melting an iron rod almost instantly by passing a large electric current through it. The home-made welding transformer to which the heavy copper connections at the left lead may be contrasted with the Boulder City transformer of Fig. 42. This one draws 30 amperes at 110 volts when delivering about 500 amperes through the 5-volt welding secondary.

is 28.6 ohms times 5000 amperes, or 143,000 volts. Even if the half-inch copper could carry the five thousand amperes without overheating (which it could not) the loss of voltage in the line would be more than a hundred thousand volts! The useful voltage would be utterly negligible in comparison with the voltage wasted in the line. The energy wasted would bear the same relation to the useful energy. Further, although we started out trying to arrange for low-voltage transmission, we actually have a high-voltage line on our hands everywhere except in the immediate vicinity of the village; for at the far end the voltage supplied to the line will have to be 143,110 volts if there is to be a useful voltage of 110 left over after 143,000 has been frittered away in transit.

Now suppose we be reasonable. Let us agree to receive the energy at 66,000 volts, and transform it to 110. At 66,000 volts, a very small current (8.3 amperes) will furnish the 550,000 watts of power desired; and the voltage-drop in the line will be only that small number multiplied by the resistance, which gives 237 volts. Thus at the far end of the line 66,237 volts must be supplied, and of this, nearly the whole, or 66,000, is delivered as useful. The waste is negligible.

So our question is answered. Without the use of high voltage, central powerhouses serving many consumers would be impracticable. Only by using great ditches full of copper, solid levees of metal, could low-voltage transmission be made feasible.

Incidentally, the illustration suggests why alternating current, not direct, is preferred for power purposes. The change of voltage from high to low, or low to high, requires transformers, and these operate only on alternating current. The dynamo generator may supply energy at a few thousand volts; this is stepped up to a value somewhere between 66,000 and 287,000 volts (the present upper limit for transmission purposes) by a transformer which feeds the energy to the line. At the receiving end, the voltage is

reduced to two thousand volts or so for distribution through the streets. Finally, outside a house or group of houses, a third transformation occurs, giving the 110 volts commonly used in homes.

In discussing transmission we have used the unit *watt*. Earlier, when electric energy was being compared with coal and gasoline, *kilowatt-hours* were used. The distinction becomes clear if we consider how to figure a monthly electric bill. A given lamp bulb may be marked 60 W 110 V. This means that the lamp uses energy at the *rate* of sixty watts if operated at 110 volts. In one hour of operation, it will consume sixty watt-hours of energy; in one hundred hours, a hundred times that, or six thousand watt-hours. This would usually be expressed as six kilowatt-hours. A kilowatt is a thousand watts; a kilowatt-hour a thousand watt-hours. If the electric rate is six cents per kilowatt-hour, the cost of operating the lamp for the hundred hours will be thirty-six cents. By multiplying the wattage of each appliance by the number of hours it runs in a month, adding the results, reducing to kilowatt-hours, and multiplying the total by the rate charged, one can estimate what the monthly bill will be.

Utilization of Electricity to Do Work

Electric motors are used by the millions to help get the world's work done. From the giant motors whirring in heavy industries to the tiny motors that spin phonograph records or turn the hands of electric clocks, one finds them at every hand. They operate fans, vacuum cleaners, electric refrigerators, sewing machines, air-conditioners, grinders, stirrers — a list too long to complete. The design of the best motor for a given purpose is not a simple matter, but the basic principle which is applied to make things move by electricity can be stated very quickly.

Consider the device that was used to illustrate the simplest

generator. It consisted of a movable coil of wire mounted between the poles of a U-shaped magnet. If used to generate electricity, the coil is rotated by force. Now, instead of forcing the coil to rotate in order to secure electricity, let a current of electricity be passed through the coil from a battery or other source of power. The current causes the coil to become a magnet. One face of the coil is a south magnetic pole, one a north. Hence the poles of the U-magnet will exert forces on the coil. In magnetism, as in electricity, unlikes attract, likes repel. The north pole of the magnet attracts the south pole of the coil; the south pole of the magnet attracts the coil's north pole. The coil tends to turn and set itself with its north pole as close to the magnet's south pole as possible, and vice versa. Now a bit of scientific strategy appears. At the time the coil reaches the position in which it tends to remain, let the direction of the current in the coil be reversed. This reverses the coil's magnetism and the coil executes another half-turn, seeking a new position of equilibrium. But at the right instant, the direction of the current is again automatically reversed by means of sliding connections at the axle, and the coil keeps on going. Like the donkey who kept running towards a meal which advanced as rapidly as he did because it hung from a pole fastened to his head, this simple motor continues to seek a position of equilibrium which the reversals of the current render untenable as soon as it is reached.

The explanation applies only to direct current motors of the simplest type. Alternating current motors are far commoner; because, as we have seen, the electricity supplied by power systems is usually alternating. A motor and a generator are very similar: each needs a magnet and a coil, one movable with respect to the other. If we force the coil to turn by connecting it to a steam engine or a water turbine, electricity may be withdrawn from the

coil for useful purposes. If we supply electricity to the coil, it turns and can do work. The details of construction of the various types of motors and generators are far too numerous to find space here. They may be looked up in books on physics or electrical engineering.

The world's work is an inexhaustible subject, but we have considered the principal means by which work of a physical nature is done in this modern age. The human body, heat engines, electric motors — all must be energized by some means, and the amount of work done cannot exceed the energy supplied. But our natural resources of energy, if wisely used, are, like our subject, inexhaustible. There will be plenty of energy so long as the atmosphere lasts and the sun keeps shining on the earth, making grains, vegetables and forests grow, carrying water vapor from the sea to the heights whence it descends as rain to run over the falls and dams again. If fertility drains from the soil, science can put it back. If petroleum fails us, liquid fuels which the chemists know how to make out of plants and coal and shale will run our automobiles. The moon, too, can be harnessed: the waters of high tide, trapped behind barriers and let fall after the tide has ebbed, will turn generators whenever we choose to arrange the setting. Plenty of energy, enough to move mountains or carve new river-beds if a whole country were in dead earnest about changing its geography; plenty of knowledge, and more coming daily, to place that energy at man's disposal. The chief unsolved problem in the field of work is to be found outside of exact science. Somewhere in the recesses of man lie motives, often conflicting motives. To what purpose, other than the mere maintenance of existence, shall the tools which science spreads before us on its bargain table be put? Physics and chemistry cannot answer that question; maybe the reader can.

Chapter 13

MATERIALS

" WHAT is it made of? " The scientist working in his laboratory, the manufacturer examining a competitor's product, the housewife making the rounds of the department stores, the child coming upon one new object after another as he investigates his surroundings — all find this question continually recurring. In Unit 2 we asked ourselves what matter itself was made of, and found it dissolving in the end into positive and negative electricity, a mysterious sea of reality upon which hardness, elasticity, color, odor, taste and other familiar properties seemed to float as precariously as the body of the magician's helper in a trick of levitation. Here we put the question again, but in a form modified to suit the present unit. What is known about materials, and how has that knowledge helped to modify the environment through which, and by means of which, civilization wends its way?

Wherever we turn new materials, and old ones dressed up, press their claims upon us. We see them, eat them, wear them, ride in vehicles made of them — and we hear about them incessantly in the vague but glowing truths and half-truths of the advertising columns. In the preceding chapter we surveyed civilization, especially our own country, from the standpoint of energy; now we take another look, from a different point of view. Here again there is a large field to survey, and very limited space at our disposal; but by selecting representative materials to illustrate the principal classifications of goods and processes we can soon come to look on our material environment with a more critical glance than that presupposed by certain kinds of advertis-

ing. One of the functions of chemistry and physics is to describe materials accurately. The scientist, the engineer, the medical man, the manufacturer want facts, and get them, when the selection of materials is at issue; and there are many signs that already a large section of the general public would prefer to select goods in the same unemotional way if the facts were provided. This chapter is not a buying guide, indeed its purpose is far more fundamental; but as we study the subject there can be no harm in keeping one eye on science's even-handed objectivity in dealing with the materials which compose the physical framework of civilization.

Taking Stock on a Tonnage Basis

In the following table we find a list of thirty-three important materials. Except for coffee, rubber and sugar, whose positions in the list have been determined by the amounts consumed, not produced, the materials are arranged in order of decreasing quantities produced annually in the United States. The list is not complete, and the order can be approximate, only. Production varies with economic conditions and with technical progress. None the less, the table gives a fair picture of the relative importance, so far as annual tonnages are concerned, of most of the materials which we use in quantities as large as forty thousand tons or more a year. Some omissions, for example brick, paper, explosives and glass, are more apparent than real; the principal materials out of which these products are made are included. What we are looking for is something other than one's favorite predilections to guide us in selecting the materials to study. We eat a few hundred tons of vitamins in this country every year, and burn several hundred million tons of coal. Obviously, quantity

is not the only criterion to be considered in appraising importance; but it has the advantage of being convenient and objective.

SELECTED MATERIALS ARRANGED IN APPROXIMATE ORDER OF THE NUMBER OF TONS PRODUCED ANNUALLY IN THE UNITED STATES

(Coffee, rubber and sugar placed according to consumption, not production.)

1. Coal	12. Sodium Chloride	23. Alcohol (grain)
2. Sand and Gravel	13. Sugar	24. Zinc
3. Clay and Stone	14. Asphalt	25. Rubber
4. Gasoline	15. Phosphate Rock	26. Lead
5. Corn	16. Ammonium Sulphate	27. Copper
6. Lumber and Pulp	17. Calcium Oxide	28. Hydrochloric Acid
7. Iron and Steel	18. Cotton	29. Wool
8. Wheat	19. Sulphur	30. Nitric Acid
9. Cement	20. Sodium Carbonate	31. Rayon
10. Potatoes	21. Coffee	32. Coal Tar Chemicals
11. Sulphuric Acid	22. Sodium Hydroxide	33. Aluminum

If one who had not studied the matter were given a list of these materials arranged in alphabetical order, and asked to make a table such as ours on the basis of casual observation, he would no doubt find many surprises when he scored his results. Coal, steel and several other familiar materials might fulfil his expectations; but we notice that the country produces more common salt (sodium chloride) than cotton; more sulphuric acid than alcohol; more sodium carbonate than wool; more sodium hydroxide than copper; more hydrochloric acid than rayon. The reagents found in the chemical laboratory are not merely materials for class exercises; many of them play roles of vital importance in scores of industries. A country's consumption of sulphuric acid has been considered by some to be the best single yardstick to use in measuring its state of civilization. (Of course, the extent to which the artistic and spiritual aspects of civilization depend on the physical remains a moot question.)

Disregarding the foods, fuels and fertilizers, which we considered in part when surveying the world's work, we find our list considerably reduced. Among the remaining materials, several *metals* in elementary form — iron, zinc, lead, copper, aluminum — are included; one *non-metallic element*, sulphur; several *acids:* sulphuric, hydrochloric, nitric; a powerful *base,* sodium hydroxide; two familiar *salts,* sodium chloride and sodium carbonate; two *oxides:* sand (silicon dioxide) and calcium oxide; and several *organic products,* including alcohol, rubber, cotton, rayon and the coal-tar chemicals.

Oxygen, silicon and aluminum loom very large in the picture presented by the table. Clean sand, which ranks second in the list, consists principally of silicon and oxygen combined together; and clay, the third item, contains aluminum, silicon, oxygen and hydrogen. Analyses show that oxygen, silicon and aluminum constitute 47.3, 27.7, and 7.9 percent, respectively, of the earth's solid crust, a total of nearly eighty-three percent. Iron contributes 4.5 percent, and four additional elements — calcium, magnesium, sodium and potassium — together account for 10.6 percent, bringing the total for these eight elements to ninety-eight percent. No other single element, aside from these eight which are so abundant, contributes as much as one percent of the earth's solid crust. Aluminum's position as the last of the thirty-three materials included in the table should not be misinterpreted. Although the most plentiful of metallic elements, aluminum has been refined commercially only in recent years, and within a generation or two will doubtless forge ahead of some of the materials which now appear above it in the table.

The Metals

Most of the ninety-two elements, like the outer planets and the vast majority of the stars, are never seen by the average person. Even among the metals, which comprise the more familiar of the two classes of elements, many are never encountered unless one makes a special investigation for the purpose. How many of the following metals has the reader ever seen: sodium, potassium, calcium, lithium, strontium, rubidium, cesium, beryllium, magnesium, cobalt, cadmium, manganese, arsenic, antimony, bismuth, ruthenium, rhodium, molybdenum, palladium, radium, uranium, thorium? Many chemists never see certain of those metals in a lifetime of professional work. Even mercury, the quicksilver of the ancients, though widely used to fill thermometers and barometers, usually excites curiosity when the opportunity to examine it in bulk, to stir it and heft it, presents itself. Chromium has recently become familiar through its use as a protective and beautifying coating for other metals. Most of us are aware of tungsten as the material out of which lamp filaments are made. Iridium and osmium are publicized in fountain pen advertising: the points are tipped with an alloy of these hard and durable metals. Iron, a silvery white metal in the pure elementary state, is seldom seen. What we call iron is usually an alloy blackened by oxide and containing small but important amounts of other elements added to improve the properties.

Even so, metals are by far the more familiar of the elements. Among the non-metals possibly only carbon, sulphur, oxygen, iodine and chlorine are widely known in elementary form; whereas every reader can mention useful applications of zinc, lead, copper, aluminum, iron, nickel, tin, gold, silver and platinum.

The usefulness of a metal depends, of course, on its properties. Many questions arise. Is the metal in question hard, like steel, or is it soft, readily scratched, like lead, gold and copper? Is it highly malleable, like copper, silver and gold, capable of being hammered or rolled into sheets? How high a temperature can it withstand without melting? Is it ductile, suitable for drawing into wires? Is it an excellent conductor of electricity, like copper and aluminum, or does it offer so much resistance that a moderate current heats it greatly, as in the case of the tungsten lamp filament? Does it conduct heat well enough to be especially useful in the construction of cooking utensils? Has it the strength requisite for use in girders to support great loads? What is its density? Is it relatively strong in proportion to weight, so that structural parts, say of an airplane or a motor bus, need not be excessively heavy? Does the metal spring back, like steel, after being deformed, or is it inelastic, like lead? Is the metal attractive in appearance, and if so, does it remain attractive when in contact with the atmospheric gases or the fumes of a great manufacturing center? How active is the metal chemically? If it rusts, does the oxide form a protective coating to prevent further oxidation, as in the case of aluminum; or does the oxide flake off and allow the whole body of the metal to be attacked? Can the metal be used safely for food containers and water pipes, or does it react with certain foods and beverages, possibly forming poisonous compounds? If the metal is satisfactorily inactive with respect to common materials, are there other materials which would speedily eat holes in the container by chemical action? How are the properties of the metal affected by melting various quantities of certain other metals with it, to make useful materials such as brass, stainless steel, coinage, the nichrome of electric stove heating elements, and other alloys? Does the metal readily take a durable

coating by the electroplating method? Does it expand like type-metal when freezing in a mold, or does it shrink away without taking a sharp impression?

This rapid-fire questionnaire shows how large and important a field of study the metals alone provide. We turn faucets and steering wheels, press brake pedals and typewriter keys, turn on lamps and waffle irons, fill up cooking utensils with whatever we wish, usually without giving a thought to special combinations of properties, the exacting requirements which a metal must meet to serve a given purpose. There are metals which act with explosive violence when water is thrown on them. The reason we can use metals so trustingly is that the manufacturers, guided by the results of scientific research, have usually selected the right materials in advance. The discovery of the correct proportions in which to melt nickel and chromium to produce the alloy now universally used in high-temperature electric heating devices — smoothing irons, ranges, portable heaters, curling irons, toasters — made the modern development of electric heating possible, and earned a fortune for the discoverer. A reasonably inexpensive metal possessing a high electric resistance was required, and it must withstand high temperatures hour after hour without melting, breaking, or oxidizing. At these temperatures an iron wire sloughs itself off in black flakes of oxide while you watch, and pure nickel grows brittle and breaks.

Many millions of research hours have gone into the discovery and measurement of the properties of metals and other substances. *The Handbook of Chemistry and Physics,* a handy reference volume, contains about two thousand pages crowded with numbers and other tabulations — and on many a page one can pick out a single number which is the foundation of an industry and a monument to human progress. Not for a long time has civili-

zation contented itself with materials as they are found in nature. New alloys artfully made to possess special combinations of properties appear almost yearly. We leave to the reader the intriguing, though at first imposing, task of thumbing through the *Handbook* to learn why a few materials in which he is interested are adapted to given purposes, while we undertake a modest sampling of the metals included in the table given above. Iron and aluminum, the first and the last metals in the list—one of the oldest and one of the newest metals of industry—are the ones we select to illustrate some of the problems encountered in this field, and how they can be solved.

Winning Iron and Aluminum from the Earth

Of the several iron ores found in the world, ferric oxide, the red rust of iron, is the principal ore mined in America. Anyone who has noticed what happens to a piece of iron when it lies abandoned in a damp place will understand why very little free iron is found native in nature. It oxidizes too readily to remain free, and the oxide does not form a protective coating. When iron rusts, it is merely reverting to a form resembling that in which it was mined. The ferric oxide, called hematite when mixed with certain other materials in mineral deposits, must be *reduced* if free iron is to be obtained. Reduction is the reverse of oxidation; it means, in this case, removing the combined oxygen. The method used to reduce the iron ore serves as a good illustration of this important chemical action.

Great quantities of coke, iron ore and limestone are arranged in layers in a huge blast furnace as tall as a seven-story building and perhaps twenty-five feet in diameter. The coke, which is principally carbon, burns fiercely in a blast of pre-heated air, pro-

ducing carbon dioxide. This reaction is an oxidation such as we studied when dealing with fuels:

$$C + O_2 \rightarrow CO_2$$

The carbon dioxide formed by this reaction filters upward through layers of hot coke and is partially reduced; that is, it gives up some of its oxygen to the carbon of the coke:

$$C + CO_2 \rightarrow 2CO$$

The CO formed by this reaction is the deadly gas carbon monoxide. The reduction is merely partial, since a molecule of carbon dioxide loses only half of its oxygen. The hot carbon monoxide now bathes the iron ore (Fe_2O_3), which contains oxygen; and since every carbon atom can readily hold two atoms of oxygen in combination, but in carbon monoxide has only one, the iron ore is reduced, giving up its oxygen to the carbon monoxide and yielding free iron and carbon dioxide:

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$$

The Fe on the right is the free element iron. In reading of the transition from carbon dioxide to carbon monoxide and back to carbon dioxide, a rapid reader might conclude that the process is going around in circles — but this last reaction has yielded free iron, which drips down in molten form and is drawn off at the bottom of the furnace.

What is the purpose of the limestone which is mixed with the coke and the ore? The iron ore is never pure ferric oxide, but is mixed with compounds of silicon. These also must be removed. Some of the extraneous matter melts and floats on top of the iron, but the silicon dioxide SiO_2 (quartz or sand) melts only at inconveniently high temperatures. Hence it is eliminated by chemi-

cal action. The limestone (calcium carbonate) decomposes in the hot furnace, furnishing lime (calcium oxide) and carbon dioxide:

$$CaCO_3 \rightarrow CaO + CO_2$$

The calcium oxide then unites with the silicon dioxide to form calcium silicate, which melts readily and floats on top of the molten iron, whence it can easily be drawn away.

This is the simple chain of chemical reactions by means of which millions of tons of pig iron are produced in the United States every year. We note particularly the twin processes of oxidation and reduction, the consumption of great quantities of coke and limestone, and the copious discharge of carbon dioxide into the atmosphere. Oxidation and reduction, like all chemical transformations, are really electric actions at bottom, and will appear again a few pages farther on in our study.

The story of the conquest of aluminum is one of the dramatic chapters of chemical history. Not very long ago aluminum was so rare that it was used to make jewelry! Its costliness satisfied the requirements of conspicuous expenditure. In 1855 it sold for about one hundred dollars a pound, a third of the normal price of gold, and as late as 1886 cost twelve dollars. But in 1886 a young American college student, C. M. Hall of Oberlin University, invented a method of obtaining aluminum which has filled millions of homes with pots and pans made of this light and serviceable metal. In the same year, by a strange coincidence, the same process was independently discovered by a young Frenchman named Paul Heroult.

Hall called electricity to his aid. Aluminum ores are, as we have seen, very plentiful, but the extraction of aluminum from the oxygen with which it is combined in the principal ore, bauxite, presented what seemed at first to be insuperable difficulties. It

FIGURE 44. Mining bauxite, the principal aluminum ore. (Bourke-White photograph, courtesy Aluminum Company of America.)

was well known in Hall's time that the molecules of many compounds break up into electrically charged ions when dissolved, each molecule furnishing one negatively charged ion, and one positive. If two plates are inserted in the solution and connected to the terminals of a battery, the positive ions are attracted to the negative plate, the negative ions to the positive. Thus electrolytic separation of the constituents of the compounds can be effected. Usually, the electrolyte is dissolved in water; but aluminum oxide, the important ingredient of bauxite, does not dissolve in water. And to turn aluminum oxide into a molten liquid requires so high a temperature that this material is widely used (under the commercial name *alundum*) to make cements, crucibles, supports for the hot wires in electric furnaces, and other products which must not melt under extremely high temperatures.

But Hall found that the aluminum oxide would dissolve in a bath of molten cryolite, another aluminum ore. A trough lined with carbon is filled with the molten ore, and heavy carbon bars are suspended in the liquid. A powerful source of direct current is connected: positive terminal to these bars, negative to the carbon lining of the trough. The ions of the aluminum oxide migrate under the electric attraction, the aluminum ions (positive) going to the negatively charged bottom of the trough, the oxygen ions (negative) to the positively charged carbon bars. The aluminum ions give up their electric charges to the lining and become metallic aluminum in the molten condition. The metal is drawn off through an opening at the bottom of the tank. The oxygen gas liberated at the other electrode combines with the carbon of the rods, which must therefore be renewed occasionally. Some minor improvements in Hall's process have been made, but the principles employed are those he discovered.

This process has brought the cost of aluminum down to twenty-

odd cents per pound. Most of the refining is done near waterfalls, where electric power is cheap and abundant. Sources of aluminum are very plentiful. Not only bauxite but kaolin and other clays, which are all rich in aluminum compounds, can be used for ores; and electric power, as we saw in our chapter on the world's work, can be multiplied many fold. The future of this invaluable material seems, like the metal itself, bright.

Iron and Aluminum in the Service of Man

The great usefulness of the two metals which we are considering results partly from their desirable properties, partly from their abundance and relatively low cost. Of course we do not always use the material which possesses the best properties for a given purpose. Platinum, nickel and chromium, for example, would sweep other materials from the field in many applications if they were sufficiently cheap. But this generation has been marked by splendid successes in the field of alloying. Two or more different metals are melted together. The resulting alloys, after suitable heat-treatment as needed, are virtually new materials, offering improvements on the good properties of the principal metal and minimizing, sometimes eliminating entirely, the undesirable attributes.

For example, a certain alloy of iron containing ten to twenty percent of chromium retains a beautiful shining surface indefinitely, without oxidizing. This is stainless steel. Another iron alloy, invar, contains 36 percent of nickel; this expands so slightly when heated that apparatus made of invar remains of practically the same size at any temperatures to which it is commonly subjected, and so is useful in making time-keeping and other devices whose accuracy depends on dimensions. Both iron and nickel

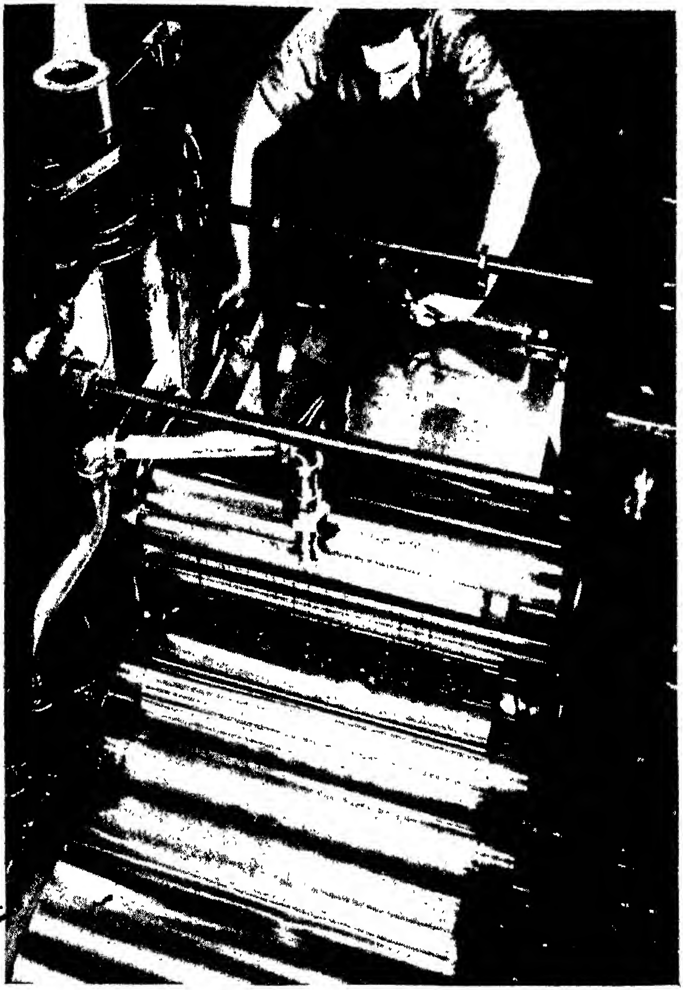


FIGURE 45. Rolling sheet aluminum into thin foil. (Aluminum Company of America.)

separately expand considerably; yet the expansion of this alloy of the two is practically nil. This shows the possibilities of alloying. The resultant properties are *not* an average of the originals. The effects produced by adding even one percent of another metal are so remarkable in certain cases that the work of experimenting with different percentages of various materials affords endless delight and many surprises. The fact that surprises are encountered so often in this field shows that we need to learn a great deal more about the intimate structural changes which occur.

Some alloys are true compounds of the metals, some are mixtures, and in some the molecules of the different metals are so thoroughly and intimately dispersed throughout the whole that *solid solutions* result, one metal dissolved in another. A few general principles of approximate accuracy are known in this field. Many researches are in progress.

Numerous other alloys are known. Recently cobalt has been alloyed with iron to yield a metal which takes and retains so strong a magnetization that one cobalt steel magnet can hold another apparently floating in the air above it, upheld by magnetic repulsion. Admixtures of tungsten, cobalt and molybdenum yield high-speed tool steels capable of drilling and cutting metal at moderately high temperatures without losing their hardness of temper. The workman does not need to pause at intervals for his tools to cool off. Adding fifteen percent of silicon to iron produces duriron, an acid-resisting metal useful for pipes and sinks in chemical laboratories and factories. Aluminum is undergoing the same sort of evolution. Approximately a hundred different alloys of iron for special purposes are well recognized, and a score of aluminum alloys.

We see that even after limiting our discussion of metals to iron and aluminum we should need a book to do them justice. In the

face of such variety, we content ourselves with a few approximate comparisons. Size for size, the best aluminum alloys now available are not as strong as the best steel; but since steel is about three times as heavy as aluminum, great savings of weight can be effected by substituting aluminum alloys for steel in the structural parts of airplanes, dirigibles, motor coaches, engines, railway trains, and moving parts generally. The extra thickness needed to gain the strength of steel is more than offset by the lightness of aluminum. To cite an example from actual practice, if a passenger motor coach is lightened by five tons by this means, without sacrifice of strength or carrying capacity, the coach possesses 680,000 foot-pounds *less* of kinetic energy when traveling at forty-five miles per hour than if it had been made of steel. Every start and stop is therefore easier and less expensive. The energy saved on every start of that coach would lift an ordinary private automobile to the top of a building some sixteen stories high. Friction, and the work of climbing hills, are similarly reduced. No doubt the future will see this advantage of lightness brought to private automobiles, with corresponding gains of economy and safeness in stopping. Centrifugal forces in rotating machinery are also diminished in proportion to the lightness of the moving parts.

Other comparisons can be made. Aluminum conducts heat approximately 3.5 times as well as does iron, hence is much better adapted to cooking and cooling applications where the heat must be conducted through the container. When rapid conduction of heat is not desired, but a metal must be used, iron is preferable. Aluminum expands about twice as much as iron when heated. The best steels are harder than aluminum alloys. In wire of a given size, aluminum is 3.6 times as good an electric conductor as iron, and weight for weight conducts more than ten times as

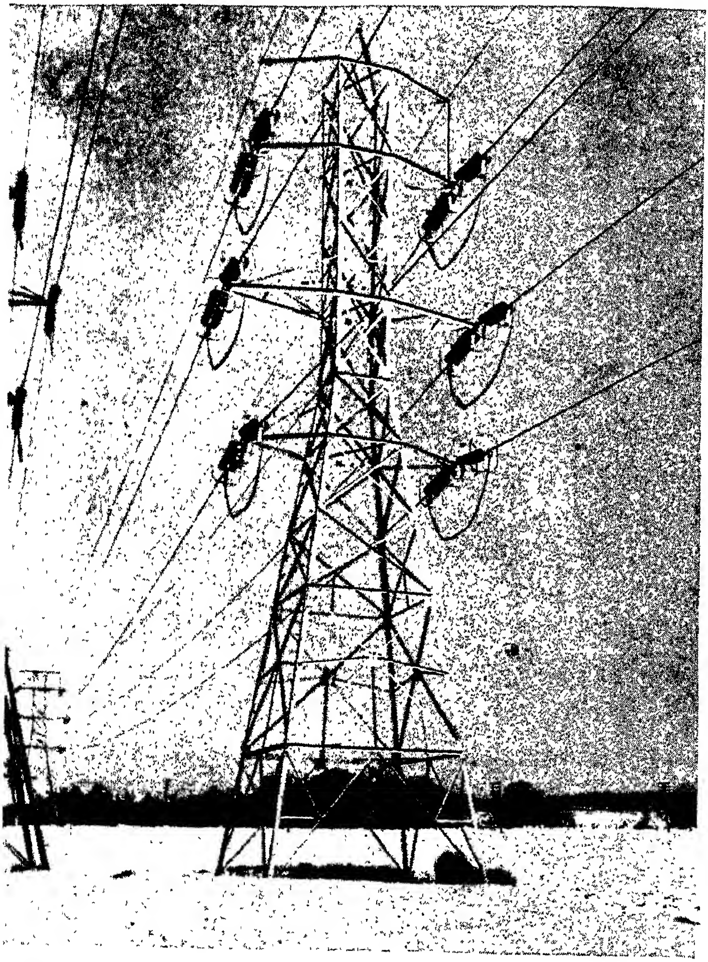


FIGURE 46. In this high-voltage transmission line, the electricity flows through aluminum cables reinforced with steel. (Courtesy Aluminum Company of America.)

readily. Indeed, aluminum is so good a conductor of electricity that it has been used instead of copper in many transmission lines. Size for size, copper is superior, in the ratio of about 1.6 to one; but since copper is more than three times as heavy as aluminum, it is not so good a conductor pound for pound. Compared in this way, aluminum is about twice as good a conductor as copper. The higher cost of aluminum by the pound is offset by the lightness; and there is less weight for the supporting poles to carry. In freedom from corrosion, aluminum is vastly superior to ordinary iron; and the stainless steel alloys which excel aluminum in this respect are at present considerably more expensive. Aluminum melts at 659 degrees centigrade, a dull red; iron at 1535. If you put an aluminum pot of food on to boil and then go off to write a book, you may find the pot lying in solidified droplets on the tray beneath the burner when you return.

A large portion of America's output of aluminum is used to unite with air bubbles in molten steel and thus eliminate the myriad of small holes which would weaken the finished product. Powdered aluminum mixed with oil or other liquids provides paint to protect metallic objects. Thin aluminum foil for wrapping food, and to insulate houses by performing on a large scale the same function (reflection of heat) that the shining silver linings of thermos bottles do on a smaller scale, consume large quantities of aluminum. Artificial gems equal to natural sapphires and rubies are made from molten aluminum oxide (alumina); traces of titanium and chromium oxides provide the color. Several complex salts called alums are used in the paper, pickling and baking powder industries, and in purifying water. Another compound, aluminum hydroxide, finds employment in a process for waterproofing cloth. A more important use of combined aluminum in the textile industry is as a *mordant* in dyeing. Mordants

are substances deposited in the fibers of textiles to absorb dyes. Cotton, especially, needs a mordant. The goods are dipped in a solution of an aluminum salt, which later, by the action of steam, yields a deposit of colloidal aluminum hydroxide in and on the cotton fibers. (Matter in the colloidal state consists of submicroscopic particles larger than most molecules but small enough to bring special forces into play. *Colloids* occur in jellies, clay, soaps, etc.; we shall meet them again.) The colloidal aluminum hydroxide acts as a mordant to absorb the dye, and thus fixes it in the textile.

Iron forms two series of compounds, ferrous and ferric, the difference lying in the proportion of iron. In the manufacture of common ink, ferrous sulphate reacts with an extract of gallnuts. These nuts are excrescences found growing on plants, especially a few varieties of oaks; they resemble nuts when dried, and since they are produced by the vegetable equivalent of sores, due to insects, worms, sometimes bacteria, are called gallnuts, or nutgalls. They are rich in an organic substance called tannin, or tannic acid. This yields, first gallic acid, then, by reaction with ferrous sulphate, the colorless substance ferrous tannate, which is the basis of common ink. This compound, when the act of writing exposes it to air, oxidizes to ferric tannate, which is black. The color of the ink in the bottle is due to a dye added merely to avoid the inconvenience of writing with an invisible liquid. Another chemical action will undo the original oxidation: ink and rust stains may be removed by soaking in ammonium oxalate solution. Other iron compounds are useful in dyeing, purifying water, killing weeds, making blueing for laundering, sensitizing paper for blueprints. Ferric oxide is widely used in the paint industry, under the name Venetian red.

Chemical Activity of the Metals

Since a metal when in use is not often surrounded by a vacuum, its chemical activity is one of the prime characteristics to be taken into account in judging its usefulness. The metal is in contact with something, even if only air or water; the possibility of chemical action is therefore present. To compare metals chemically, we fortify ourselves with a few facts about chemical activity in general, especially what happens when metals make contact with solutions containing dissolved compounds of the kinds known as acids, bases and salts. Aluminum, for example, reacts with acids and hot bases, and therefore should not be used as a container for such solutions. The bright new appearance which aluminum pans present after certain uses shows that chemical action has occurred. After our frequent references to the electric nature of matter, there will be no occasion for surprise if our discussion of chemical activity deals largely with the minute electrified wanderers called ions into which the molecules of all acids, bases and salts dissociate when dissolved in water.

Three *acids* — sulphuric, nitric and hydrochloric — appeared in the table of important materials at the opening of this chapter. The formulae of these acids — H_2SO_4, HNO_3, HCl — show that they all contain hydrogen. All acids contain hydrogen; but so do many organic compounds, such as sugar or cellulose. The distinguishing characteristic of acids is not that they contain hydrogen, but that *they all yield positively charged hydrogen ions when dissolved.* It is these positively electrified hydrogen ions which give acids their sharp, biting taste. The characteristic ingredient of vinegar, for example, is acetic acid.

The table also contained one of the *bases,* sodium hydroxide,

commonly known as caustic soda or (when dissolved) ordinary household lye. All bases are characterized by the negatively charged hydroxyl ions (OH) which they yield when dissolved in water. Here the ion consists of two atoms, oxygen and hydrogen, bound together. These negative hydroxyl ions are doubtless responsible for the soapy taste of hydroxides.

Salts are the third type of inorganic compounds which form ions when dissolved. Common table salt is the most familiar of the salts. Suppose we put some of the sodium hydroxide (NaOH) of the preceding paragraph into a water solution of one of the acids, say hydrochloric acid (HCl). Positive hydrogen ions of the acid unite instantly with negative hydroxyl ions of the lye, forming water and leaving the remaining ions of the two kinds of molecules to unite to form salt. The equation shows what happens:

$$HCl + NaOH \rightarrow H_2O + NaCl$$

Water and sodium chloride, the salt, are formed by this reaction. This particular salt remains in solution; but if in another reaction of this type the salt formed is insoluble, it precipitates out as a solid and the action proceeds to completion. Other well-known salts are sodium carbonate (washing soda), magnesium sulphate (Epsom salts), copper sulphate, borax, baking soda. Salts always contain a metal, and the remainder of the molecule is formed of the atoms that are left over when the hydrogen and hydroxyl ions of the appropriate acid and base combine. This typical reaction of an acid and a base adds a third general type of reaction to our repertoire. We have already noted examples of oxidation and reduction; now we see that an acid and a base tend to neutralize each other. This principle is kept in mind in the practice of medicine, in dealing with spilled chemicals, and in many industrial operations.

It is important to note that salts, though formed by the reaction of an acid and a base, do not necessarily give neutral solutions. The solution may be acidic, basic, or neutral. Litmus paper is a handy indicator: it turns red when moistened with acids, blue with bases. Sodium bicarbonate (baking soda) is a salt, not an acid or hydroxide; but when dissolved in water it gives a weakly basic solution. The sodium bicarbonate ionizes when dissolved, and some of the ions combine with the hydrogen and hydroxyl parts of water molecules.

$$NaHCO_3 + H_2O \rightleftarrows NaOH + H_2CO_3$$

The equation shows sodium bicarbonate combining with water to form sodium hydroxide, a *strong* base, and carbonic acid, a *weak* acid. The double arrows indicate that the action is reversible; an equilibrium results in which all the compounds are present. What concerns us here is that the hydroxyl ions of the strong base are more numerous than the hydrogen ions of the weak acid, hence this salt gives a basic solution. That is why it serves to counteract stomach acidity. Certain advertisements stress the importance of keeping the bodily system alkaline (basic); but a medical man would probably point out that the hydrochloric acid of the stomach plays a part in digestion. A single principle of chemistry is not enough to furnish a sufficient guide in health matters.

Solutions which contain ions are called electrolytes; they conduct electricity. A versatile second-year physics student once injected an original note into her laboratory work by applying electrolytic action to invent a simple device for closing windows automatically whenever rain started to come into the room. The two wires of an electric circuit were fastened to a blotter previously soaked in strong salt water and then dried. When rain moistened

The cycle is now complete; for on looking at the equation showing how the lime was formed in the first place, we see that we have the original material again, calcium carbonate. Hard stone that took countless billions of living organisms and the slow processes of geological ages to make, has been quickly unmade and re-made by the near-magic of chemical actions. It is now stone again, stone made to order while one waits, and made to fit. It fits the bricks, it fits every grain of sand that was added.

Since mortar requires carbon dioxide in order to harden, it must remain in contact with the atmosphere while setting. For many purposes, a cement that will harden under water, out of contact with air, is desired. The effort to meet this need led, a little more than a century ago, to the discovery of Portland cement. The role now played by cement may be judged by noting its prominent position in the table. Limestone and clay are mixed together and heated to a high temperature. The limestone ($CaCO_3$) gives off carbon dioxide, just as it does when heated to make lime for mortar; and the calcium oxide which results combines with the aluminum-silicon compound present in clay to form a number of compounds, of which calcium aluminate and calcium silicate are the most important. This mixture is pulverized, bagged and shipped, and when it is subsequently mixed with sand and water and left to set, the hardening is produced by a chemical action which requires water but not air. In one of the principal reactions, the calcium aluminate, $Ca_3(AlO_3)_2$, combines with water:

$$Ca_3(AlO_3)_2 + 6H_2O \rightarrow 3Ca(OH)_2 + 2Al(OH)_3$$

The atoms are all there, the same on the right as on the left, but they have been rearranged, and man's purposes are served. The calcium hydroxide and aluminum hydroxide produced by this reaction come from one of the two principal ingredients of the

cement. The calcium silicate does not enter into this reaction, but is cemented into a hard mass by the products to the right of the arrow. The calcium hydroxide crystallizes in time, and the aluminum hydroxide helps to fill the pores. Thus stone is built up around steel in modern buildings, foundations are laid, garages floored, dams made for irrigation and the generation of electric power, and thousands of miles of smooth durable highways spread through the land to destroy provincialism, revolutionize business economy, and change the personal habits of a nation.

Thus far in this section silicon has shared the honors with aluminum. Oxygen, hydrogen and carbon have figured prominently, but by this time we are so used to these important elements that they are in danger of being taken for granted. Calcium captured the spotlight in the chemistry of fastening bricks together, and gave silicon and aluminum a good run for the lead in the story of Portland cement. Now aluminum leaves the stage for a well-earned rest; the veteran sodium enters to take its place; calcium and oxygen stay on — and silicon still holds the leading role!

What manner of matter *is* this ubiquitous element, silicon? Before studying its most useful contribution to civilization, the transparent solid solution called *glass,* let us take a closer look at silicon. Until 1823 silicon had never been obtained as an element, and for many years thereafter it would have cost more than a thousand dollars a pound if anybody had bought that much. Now huge furnaces heated by electric arcs produce it for a few cents a pound by heating silicon dioxide (quartz rock or sand) in intimate contact with coke. The carbon of the coke robs the rock of its oxygen, forming the poisonous gas carbon monoxide and freeing the silicon. Lumps of silicon are gray-black, resembling graphite in appearance. The element is indifferent to all acids except a mixture of nitric and hydrofluoric acids; it reacts with hot sodium hy-

FIGURE 47. Raw materials in the glass works. The ingredients are mixed in the correct proportions to make glass of the desired properties. (Courtesy Corning Glass Works.)

droxide to liberate hydrogen. This method has been used on a large scale to secure hydrogen for lighter-than-air dirigibles. Silicon's readiness to unite with oxygen has no doubt been inferred from our frequent references to silicon dioxide. Limestone is the only common rock that is not a compound of silicon. Large amounts of elementary silicon are used in making steel alloys for electric transformers and for acid-resisting sinks, drains and receptacles.

In 1885 silicon carbide, a compound of silicon and carbon, was discovered by means of an electric experiment: one electrode became covered with jewel-like crystals of dazzling beauty. For a while the discoverer sold his new product as gems, at five hundred dollars a pound; but soon, looking farther ahead, he reduced the price to ten cents a pound and launched the carborundum industry. Carborundum is the trade name of silicon carbide, SiC. This hard abrasive material, nearly as hard as diamond, now shares with emery (a granular mineral called corundum composed of oxides of aluminum and iron) the task of doing the grinding and polishing which enable the working parts of the high-speed motors and machines of today to fit with their beautiful precision.

To make common glass, white sand (SiO_2) is mixed with limestone ($CaCO_3$) and sodium carbonate (Na_2CO_3), and the whole heated well above twelve hundred degrees centigrade. We have already noted that limestone gives off carbon dioxide gas when sufficiently heated, yielding calcium oxide. The sodium carbonate behaves similarly, producing sodium oxide; and soon the white-hot molten mass contains the oxides of silicon, calcium and sodium. A chemical action aids the heat in liberating carbon dioxide; the oxides react; and finally, among other silicates, an important compound containing silicon, calcium and oxygen in the proportions Na_2O, $3CaO$, $6SiO_2$ is formed.

FIGURE 48. The molten glass poured from the half-turned melting pot is shaped between rollers on its way to the annealing lehr. Note the puddle of glass formed by the overflow from the casting table. (Courtesy Pittsburgh Plate Glass Company.)

The purpose, of course, is to produce a transparent solid. What happens when this molten compound cools is therefore all-important. Consider, for example, some sugar dissolved in water. The solution is transparent. Let it be made thicker and thicker by boiling water away, then watch it as it cools. Solid sugar separates out from the solution in white crystals. The crystalline solid is opaque; the solution it came from was transparent. If glass behaved similarly, it would not be the transparent material that we know. But as the molten mass cools, the compound merely grows thicker and thicker without crystallizing, until finally the solution is so viscous that it is hard. Properly speaking, the cold hard glass of a windowpane is still a solution. By how narrow a margin this blessing of transparency is gained can be judged by softening a glass tube repeatedly in a flame. It soon becomes devitrified, or, to coin a word, deglassified. The loss of its transparency is due to crystallization.

The art of glass-making is at least five thousand years old, but in recent years physical science has attacked the problem and wrought notable improvements. Special glasses for special purposes are made by varying the kinds and proportions of the ingredients. Ordinary glass cracks when suddenly heated or cooled; this is due to the sudden change of size of *part* of the object. To obviate this inconvenience, chemists of the Corning Glass Works in this country perfected a glass whose coefficient of expansion is only one-third as great as that of common glass, 0.0000036 against 0.0000107 centimeters of expansion per original centimeter per degree centigrade rise of temperature. On that number, which fills so small a space in the *Handbook of Chemistry and Physics*, and on a moderate elevation of the softening temperature, the *Pyrex* industry has been founded. Crookes glass for spectacles is specially formulated to absorb the ultra-violet, to protect tender

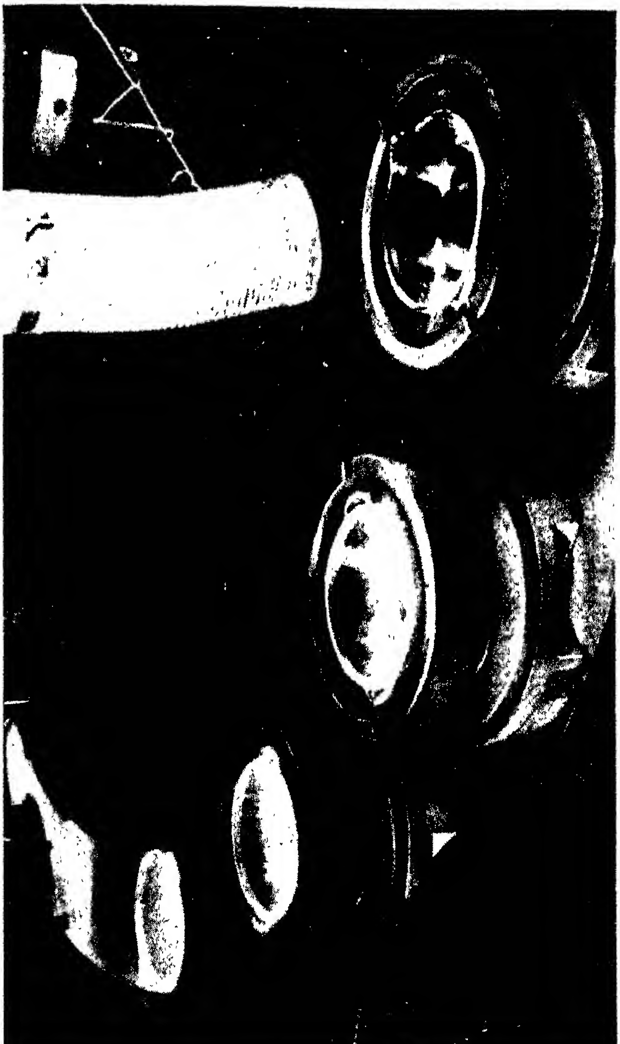


FIGURE 49. Glass ovenware in the making. The molten Pyrex is automatically pressed into shape by a plunger. Glass having a low coefficient of expansion is a practical, though not perfect, substitute for expensive fused quartz. (Courtesy Corning Glass Works.)

eyes. Certain other glasses are specially made to transmit the ultra-violet; these are still expensive. A half-century ago Ernst Abbé and Carl Zeiss of Germany calculated what the optical performance of lenses and prisms would be if glasses possessing hitherto unknown combinations of properties could be discovered. The results showed that great improvements in telescopes, microscopes, spectroscopes and other optical instruments would result. After laborious researches, the hypothetical glasses became real — and we have our good modern instruments. No longer is it necessary to put up with images flushed and falsified with spurious colors, or seriously distorted. Chemistry and physics together have put an end to those drawbacks, except in so-called bargains. Germany pioneered in this work, but lost her ascendency as a result of the World War. Under the press of necessity, America became independent of German optical glass and took the lead.

One day pure fused transparent quartz — pure silicon dioxide — may become cheap enough to come out of the laboratories and into the homes of the land. This amazing substance is more transparent than glass, especially to the ultra-violet; it remains hard at temperatures that turn glass to a liquid; and it expands and contracts so slightly that a red-hot quartz dish can be plunged into cold water without cracking. Great strides have recently been made towards quantity-production; but fused quartz is still too expensive by far to displace Pyrex cooking ware, or to glaze our homes with crystal-clear windows that will transmit the health-giving ultra-violet in sunlight. But the raw materials are abundant, and — who knows? This age has seen royalty turn into citizens, and has watched aluminum and silicon carbide leave the blue velvet of jewelry stores to help make pots, airplanes and grindstones.

Soap — and Colloidal Action

As our modest sampling of the subject progresses, we notice that, one after another, the materials listed in the table at the opening of this chapter appear in the discussion. We have just seen that the manufacture of glass requires large quantities of sodium carbonate, the twentieth item in the list. Calcium oxide figured prominently in the accounts of glass, cement and mortar. The high rank of sand and clay in the table has been accounted for. The raw metals have been considered, with emphasis on iron and aluminum. Food, fuels and fertilizers received attention in the preceding chapter. Partial justice has been done to the important subject of acids, bases and salts, which were considered from the standpoint of chemical behavior rather than large-scale practical applications. Now the powerful base, sodium hydroxide, appears again. The carbonate of sodium, a salt, helps to give us glass; the hydroxide of the same intensely active metal is central in the manufacture of that homely material, soap.

Of soap, as of glass, there are several varieties. The soaps sold by the millions of bars every year are sodium salts of certain weak organic acids called fatty acids. These acids are present in animal and vegetable fats and oils. The sodium comes from sodium hydroxide. The latter comes from — common salt! Surely nobody has inferred from our list that we sprinkle enough salt on our food to place sodium chloride above sugar and cotton. One of the most important chains of chemical actions, from an industrial point of view, is that which leads from common salt to sodium hydroxide. There are several routes; here is one of the best. Salt dissolved in water is treated with ammonia (remember the fixation of nitrogen) and carbon dioxide:

$$NaCl + H_2O + NH_3 + CO_2 \rightleftarrows NaHCO_3 + NH_4Cl$$

The products on the right are *sodium bicarbonate,* familiar as baking soda and a mildly alkaline medicine; and ammonium chloride, used in soldering and in the manufacture of electric dry cells. By heating, the sodium bicarbonate is decomposed into water, carbon dioxide and *sodium carbonate.* This last, we remember, is used in glass-making. Finally, by treating the sodium carbonate with calcium hydroxide (slaked lime), the *sodium hydroxide* needed in soap-making is obtained, together with some calcium carbonate.

Sodium hydroxide can also be obtained directly from salt by passing an electric current through salt brine. The choice between alternative processes often hinges on the demand for the by-products. This electrolytic process produces chlorine and hydrogen as by-products. In time of war, the poison gas chlorine is likely to be the objective, with sodium hydroxide the by-product.

Once the sodium hydroxide and fat or oil are at hand, soap can be made. Soap has been used since about the second century of the Christian era. Soap-making flourished commercially in Marseilles as early as 1000 A.D., and gained a foothold in England in the fourteenth century. Until about two generations ago, however, soap-making was an art which every rural swain expected of his bride. Nowadays, in the larger plants, a single kettle may hold enough hot oil and sodium hydroxide to make a two-hundred-ton batch of soap. No one would wish to be in the vicinity if the bottom fell out of that steaming kettle. The principal products of the reaction are soap (sodium stearate $NaC_{18}H_{35}O_2$) and glycerine, whose formula is $C_3H_5(OH)_3$. Another typical soap, sodium oleate, has the same formula except for two atoms fewer of hydrogen. Still another is sodium palmate. The complex nature of the fat molecules may be judged by noting that they give these products by reacting with the relatively simple com-

pound, NaOH. The glycerine is an important by-product; it is used in the manufacture of explosives, and is one of the best anti-freeze agents to lower the freezing point of water in automobile radiators.

A thousand-and-one interesting details for which we have no space will be discovered in any comprehensive account of the manufacture and uses of soap. The dissolving in alcohol and re-hardening to make transparent soaps; the beating in of air bubbles to increase the volume and obtain cakes that float; the use of fillers such as water glass, some of which help to soften water and promote the formation of suds; the addition of dyes and perfumes; the objectionable scum formed when the calcium or magnesium salts present in hard water react with the soap, changing the formula, for example, from the soluble soap $NaC_{18}H_{33}O_2$ to the insoluble compound $Ca(C_{18}H_{33}O_2)_2$ — these and related matters may be found in comprehensive books of chemistry. The fundamental question seems to be, not why one soap is slightly different from another, but *why any soap cleans at all.*

If a steel needle is coated with a thin film of grease by wiping with an oiled rag, and then laid very gently on the surface of some clean water, the needle, apparently violating Archimedes' principle, floats. Like some insects that walk on water, the needle is held up by a force which is exerted in greater or less degree by all liquid surfaces — a force tending to pull the surface into the smallest area that will contain the liquid. The converse of this needle-floating effect can also be observed: merely sprinkle drops of water upon a smooth greasy surface. The drops do not wet the surface, but are pulled into nearly spherical shape by their own *surface tension.* But if the grease-clad needle that we started with is laid on the surface of some very soapy water, it does not float. The dissolved soap decreases the surface tension of the water and thus

enables the water to wet the needle. A floating toothpick with a fragment of camphor stuck on one end moves as if it had a propeller; the dissolving camphor at the rear lowers the surface tension locally and unbalances the forces. The lowering of the surface tension by dissolved soap is one of the principal reasons why soap cleans, and also accounts for the ease with which soapy water forms suds or lather — masses of tiny bubbles. The less the surface tension, the less the sidewise pull that tends to flatten the surface and thus destroy the round shape of any bubbles which may form on the surface.

But surface tension alone does not explain the remarkable detergent (cleansing) effect of soap. Colloidal action must be taken into account. Earlier in the chapter we noticed the use of a colloidal deposit of aluminum hydroxide as a mordant in dyeing cotton goods; the deflocculating effect which tannin and certain other substances produce in a colloidal solution of clay in water; and a similar action of egg yolk in mayonnaise dressing, which prevents the coalescence of the colloidal droplets of oil suspended in vinegar. Dirt has been defined as matter out of place; in this sense, grease is often dirt, and moreover, it readily holds dust and other extraneous matter. By emulsifying the grease, turning it into a colloidal solution of tiny droplets and preventing these droplets from re-coalescing into larger aggregations, soap performs one of the most useful functions.

Colloidal solutions are not, in the true sense of the word, solutions. To avoid inconsistency, they are sometimes called sols. When sugar is dissolved in water, a *true solution* results: the sugar breaks up into its molecules. The sugar is dispersed as molecules among molecules; no individual particles can be detected with even the best microscopes, and *none will ever settle out* unless evaporation of water, or possibly cooling of the solution, forces

some sugar to crystallize. In another experiment, we find that some cold water which has been given a milky appearance by kneading a cloth bag of flour in it, gradually clears if allowed to stand: the starch that came from the flour settles to the bottom. The milky water in this case was not a solution, but a *temporary suspension*. Between these two extremes stand colloidal solutions. If the starch granules in the water are broken up into smaller (colloidal) particles by boiling, they still do not dissolve, but the liquid remains cloudy. Or if a little pure clay is shaken vigorously with water to which tannin has been added to serve as a deflocculating agent, the clay particles which give the water a milky appearance show little tendency to settle out. They are small enough to be held in suspension by the molecular agitation of the water and by mutual forces of electric repulsion, yet are larger than molecules—large enough, in fact, to be detected individually by means of the *Tyndal effect.* Suppose the colloidal solution is placed under a microscope and a narrow intense beam of light passed through the solution *from the side.* The direct beam does not enter the microscope, but the colloidal particles in its path scatter some of the light upwards into the microscope (the Tyndal effect) just as dust particles in the air scatter sunlight sideways from a narrow beam coming through a hole in the windowshade.

The microscope reveals the colloidal particles as scintillating points of light. The apparatus is called the ultra-microscope, since the particles are not seen as images showing size and shape. They can be localized by eye merely as flashing points darting to and fro with an irregular random motion to which we have often referred in these pages, the Brownian movement.

Colloidal particles range in size from about one to a hundred ten-millionths of a centimeter, or millimicrons. This is larger

than most molecules, but smaller, for example, than blood corpuscles. The red corpuscles of human blood are about 7500 millimicrons in diameter, or about seventy-five times as large as the largest particles usually classed as colloids. Other substances, however, do exist in the bodily juices as colloids, and play important roles in the processes of life.

Colloidal particles are usually found to be electrically charged. This fact is capitalized in a number of ways. Similar electric charges, we remember — for example, two positive charges — repel each other; and opposites, a positive and a negative, attract. In the Cottrell smoke precipitator, the colloidal particles of carbon which form the smoke are attracted by an electrically charged metal plate mounted in the smoke stack. The effect of turning the electricity on and off is very striking: one moment black clouds are billowing forth from the chimney; the next moment, when the force of electric attraction is applied, the smoking ceases. The advantages of this method of keeping an industrial city clean are obvious. In this process, the effectiveness is increased by electrifying the smoke colloids artificially before they reach the electrified plate; they pass a pointed metal electrode from which they gain charges opposite to that of the plate.

Another illustration is the separation of soap from water and glycerine in the huge kettles in which it is manufactured. Here the natural charges of the soap colloids are depended on. Common salt, an *electrolyte,* is thrown in. The electrified ions formed when the salt dissolves neutralize the electric charges of the colloidal particles of soap, and thus, by destroying their mutual repulsions for one another, facilitate their coalescence into a compact curd at the top of the kettle. This action of electrolytes — the ion-forming substances known as acids, bases and salts — in causing colloidal particles to coalesce or coagulate out of a solution is

just the reverse of the deflocculating effect of tannin in clay solutions, or the emulsifying action of egg yolk in mayonnaise dressing. Acetic acid is useful to coagulate the colloidal casein which is suspended in milk, and pectic acid (from pectin) is used to promote coagulation of fruit juices into jelly.

Merely to catalogue the applications of colloids would require pages. Gelatine and glue, for example, do not dissolve in water; they form colloidal suspensions. The fact that skin is a colloid is capitalized in certain tanning processes. Coal pulverized to colloidal size and suspended in oil is already being piped around as a substitute for fuel oil. Both the gelatine of a photographic film, and the sensitive silver bromide or iodide embedded in it, are colloidal in nature. It would be folly to beguile ourselves into thinking that these few paragraphs can accomplish much beyond making us aware of the importance and the interest of this relatively new branch of physical chemistry. A great deal is known, but much remains to be learned. Since the determining factor is merely the size of the particles, the boundaries of the field are indefinite.

The behavior of colloids completes the explanation of the cleansing effect of soap. The first action we considered was the conversion of grease into a colloidal emulsion — an action made possible by the effect of soap in decreasing the surface tension of the water. The second action is strictly colloidal. There is a force of attraction between the colloidal particles of soap and the fine powders which form grime in the crevices of the skin. If the soap colloids greatly outnumber the particles of grime, the latter are carried away. The validity of this explanation is attested by an interesting experiment. If a dilute soap solution is shaken with some infusorial earth (a fine white powder) the tables are turned. The powder cleans up the soap solution! On filtering the mixture,

clear water is obtained, showing that the soap colloids, though small enough to pass readily through the filter, have remained behind attached to the particles of infusorial earth. A similar action of powdered charcoal is widely used to clean liquids of coloring matter.

Creative Chemistry

Creative Chemistry is more than the title of a good book by Dr. Slosson; it is an expression connoting what the average person seems to expect of a chemist. When the chemist reaches into nature's hat and pulls out, not a commonplace rabbit, but a brand-new substance that no man has ever seen before, we are apt to think he is performing his principal function. Ordinarily, we give little thought to the indispensable work of refining the commoner raw materials; testing and purifying drinking water; analyzing prepared foods, beverages, drugs, soaps, cosmetics, insecticides, gasoline, paints and fertilizers to guide the manufacturer and protect the consumer. When a man buys a radio set, he cannot tell by a casual inspection to what extent the probable life of the condensers, transformers and other concealed parts may have been shortened in order to gain an advantage of cheapness or compactness over a competitor; but he can at least tell whether the cabinet seems sturdy and presentable, whether the tone, volume and selectivity measure up to reasonable standards. But the person drawing a drink of water from the faucet in a great city, or the farmer buying a sack of fertilizer at the village feed store, must drink or buy entirely on faith. He is utterly defenseless unless a chemist has been busy somewhere in the background. The water might be clear, sparkling and palatable, and still contain enough poison to kill a man; and the sack of fertilizer, for all the

farmer could tell by the appearance, might conceivably consist of nothing more useful to the crops than a mass of suitably disguised sawdust.

For every chemist engaged in the spectacular pioneering which enriches civilization by creating hitherto unknown substances, there are scores working day after day in the laboratories of factories and in the municipal, state and federal testing bureaus, protecting the manufacturer in his purchases of materials, guiding him in the preparation of his finished product, and protecting the public's health and the consumer's dollar as effectively as the laws which Congress can be persuaded to put on the books permit. In terms of quantity, the chemist's work, like the topics to which this chapter is largely devoted, deals principally with the commoner aspects of our material environment.

Even so, our concluding sub-title, creative chemistry, might just as well have been used to caption the entire chapter. In the familiar fields of the common metals, acids, bases, salts, soap, cement, glass and a long list of other materials the creative hand of chemistry is as surely at work as in the manufacture of rayon, bakelite, novocaine, Duco, stainless steel, aspirin, pyralin, chloramine, insulin, TNT or the alizarin dyes. Creative chemistry, like another stock phrase, cruel and unusual punishment, seems to change its meaning with the times. Electrocution and lethal gas chambers would doubtless have seemed cruel, and certainly unusual, to the functionary who struck off the head of Mary, Queen of Scots. The chemist who first extracted the now-familiar metal aluminum from the clays which hold it in well-nigh inexhaustible quantities was creating a new material as surely as did Alfred Nobel, founder of the peace and other prizes, when he first made dynamite. Aluminum is not found free in nature, but is concealed by that most perfect of camouflages, chemical combination. Sul-

phuric acid, on which scores of industries depend for their existence, is not native in earth, water or air; nor are dozens of other prosaic materials which the reader of this chapter could cite. The logical conclusion seems to be, that when people talk about creative chemistry, what they really have in mind are merely the more recent or intriguing products of a science that has been doing business at the same stand for a long time.

Accepting this interpretation, we round out our study of materials by considering very briefly several of the less familiar processes, especially certain products obtained by means of reactions involving acids, cellulose and the coal tar chemicals. These important raw materials are included in the table of the large-quantity items given at the beginning of the chapter. With *cellulose,* a vegetable product, we are already familiar. Clean cotton, we remember, is nearly pure cellulose, and wood is largely cellulose. The production of *coal tar,* a residue obtained when coal is distilled destructively to obtain coke, ammonia and other materials, was mentioned in the preceding chapter. How *sulphuric acid,* the most important of the acids, is obtained, one may possibly guess from its formula, H_2SO_4. Hydrogen, sulphur and oxygen are required. The first and last are plentiful in water, the last in air also; and as for the sulphur, the traveler in Texas or Louisiana can see it in great yellow mountains which are formed where it solidifies at the mouths of the pumps after having been melted underground by superheated water forced at great pressure a tenth of a mile into the earth. Burning the sulphur yields sulphur dioxide, a gas. By means of a catalyst, this can be made to react with oxygen to form sulphur trioxide; and the trioxide, when dissolved in some of the sulphuric acid solution previously formed, gives more of the acid. Great quantities of sulphuric acid are used in manufacturing food for the soil: it converts ammonia from coke

FIGURE 50. Chemistry creates new materials. The Lucite being polished here is one of the newest. Lucite is a transparent thermoplastic resin which looks like glass yet can be readily sawed, cut, drilled and polished. (Benedict Frenkel Photograph, Courtesy E. I. du Pont de Nemours & Co., Inc.)

ovens or nitrogen fixation plants into ammonium sulphate, one of the most important fertilizers, and transforms the phosphate rock of Florida and other states into soluble calcium acid phosphate, known as superphosphate fertilizer. Sulphuric acid is also used in making other acids — for example, *hydrochloric acid,* by reacting with common salt — and in the manufacture of paper from wood pulp, storage batteries, galvanized iron, leather, and products too numerous to consider here. *Nitric acid* can be made directly from ammonia, but in this country is still largely manufactured by the interaction of sulphuric acid and sodium nitrate (saltpeter).

Our present assortment of raw materials includes some inorganic substances, the acids; the organic vegetable matter cellulose; and the organic derivatives of coal tar, of which the most important are benzene, toluene, naphthalene, anthracene, phenol, creosote, xylol and pitch. Several of these derivatives are familiar to all. Carbolic acid, for example, is merely another name for phenol; and naphthalene is the material of which moth balls are made. If we went into business with this inventory of raw materials, what are a few of the products that we might expect to make?

Merely to itemize the possibilities would require several pages. Suppose we start with *carbolic acid.* A solution of this white crystalline solid is used as a strong though rather harsh antiseptic and *disinfectant.* Treat the solid with a mixture of nitric and sulphuric acids, and one secures picric acid, which is at once one of the most powerful *high explosives,* a permanent and fashionable *yellow dye* for textiles, and a medicament sometimes used as an *antiseptic* covering for burned skin. Or utilize the carbolic acid in a reaction with formaldehyde, in the process discovered by L. H. Baekeland. This gives the familiar material *bakelite,* a beautiful,

hard, insoluble, non-inflammable, durable substance used to make radio panels, electric insulators, phonograph records, beads, knobs, cigarette holders, buttons, billiard balls, dolls, decorative boxes of many sorts, bearings and other machine parts, and scores of other useful articles. By subjecting the carbolic acid from the coal tar to still another treatment, drug manufacturers obtain, first salicylic acid, then acetylsalicylic acid, otherwise *aspirin,* to whose merits so many hours of radio time have been dedicated.

Turning to *toluene,* a benzene-like liquid obtained from coal tar, we find several possibilities. When treated with the same acids that caused carbolic acid to yield picric acid, toluene also produces a *high explosive:* trinitrotoluene, better known as TNT. Or use the toluene in a succession of reactions requiring concentrated sulphuric acid, chlorine, ammonia and oxidizing agents, and one can secure *saccharin,* a white crystalline powder five hundred times as effective a sweetening agent, gram for gram, as sugar is, yet so lacking in nutritive value that stringent laws prohibit its use as a substitute for sugar in commercial products. Physicians sometimes prescribe saccharin to ameliorate the taste of food for sufferers to whom sugar is forbidden. Toluene is also one of the important chemicals used in the manufacture of *dyes.*

Cellulose, like toluene and carbolic acid, yields a high explosive when treated with nitric and sulphuric acids. The nitric acid reacts with the organic compound; concentrated sulphuric acid absorbs the water formed by the reaction and thus hastens the action. Acid is principally what nations fight with, in modern warfare; but of course the acid is used as a raw material in the manufacture of products that are handier for throwing purposes, and deadlier. The product in this case is *guncotton,* another explosive of devastating potentialities. By subjecting cotton somewhat less thoroughly to the acid treatment, *pyroxylin* is obtained — a hard

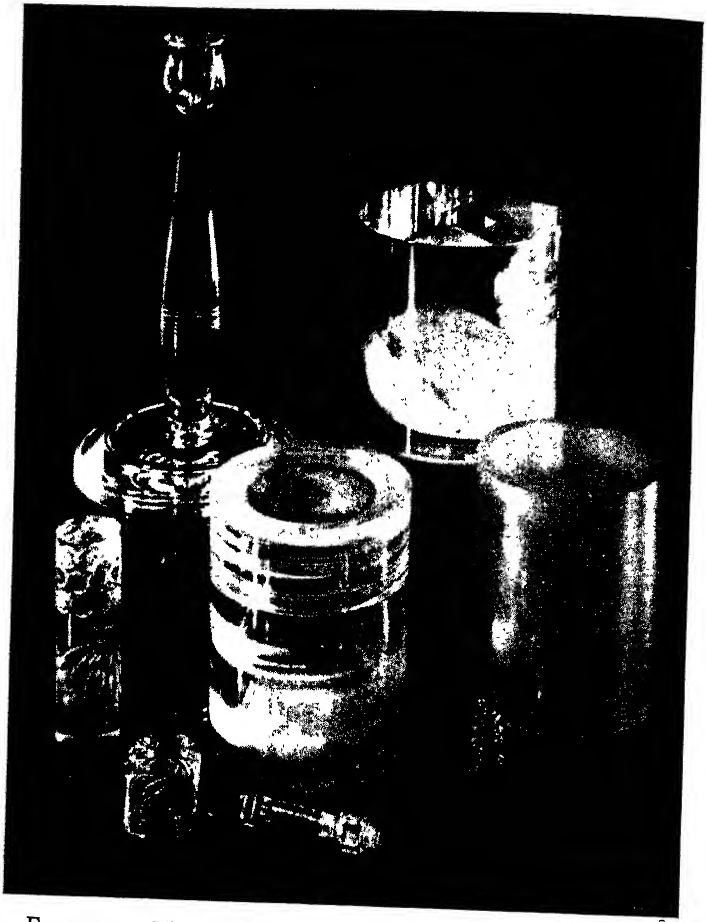


FIGURE 51. These articles are made of Lucite, one of the chemist's newest creations. At low temperatures Lucite resists the action of alcohol, water and common oils and acids; it has the same index of refraction as crown optical glass; it is highly transparent to visible light and moderately transparent to the near-ultraviolet; and can readily be worked with tools or by moulding. Technically, this new material would be described as a polymerized derivative of methacrylic acid — an organic compound. (Courtesy E. I. du Pont de Nemours & Co., Inc.)

material which, after being suitably colored, is used as imitation amber, ivory and ebonite to furnish handles for knives and toilet articles, receptacles for the vanity dresser, and numerous other articles. If the handle of a toothbrush becomes sticky when moistened with alcohol, it is probably made of pyroxylin. Touch a match to the handle to make sure; pyroxylin is highly inflammable. The close relation between pyroxylin and the high explosive guncotton led to some interesting surprises, and a few accidents, in the early experimenting. If some pyroxylin is dissolved in a mixture of alcohol and ether, *collodion* is formed. This liquid is familiar to many as a quick-hardening cement or filler used to protect minor cuts and abrasions on the fingers, and to repair mistakes in mimeograph stencils. Lessen the viscosity of collodion by heating it with mildly alkaline agents, color it, and one has the principal ingredient of modern pyroxylin lacquers; for example, *Duco*. Or mix the original pyroxylin with camphor and alcohol and roll it into sheets of *celluloid*, of which millions of linear feet have run through the motion picture projectors of the land. To secure a less inflammable film, return to the cellulose that we started with in this paragraph and treat it with anhydrous acetic acid. By this means cellulose acetate is obtained, a material used to make what is known as *safety film*.

The textile manufacturer puts cellulose to still another use. He treats spruce wood with sodium hydroxide and carbon disulphide in succession, and sprays the resulting solution (viscose) through fine holes into a bath containing sulphuric acid and other substances. The reactions that take place give sleek threads of *rayon*, a silk-like material to which no feminine reader, at least, needs an introduction. A very similar process, in which the viscose comes through slits instead of holes, and a bath of sodium chloride and other salts is interposed ahead of the final acid bath,

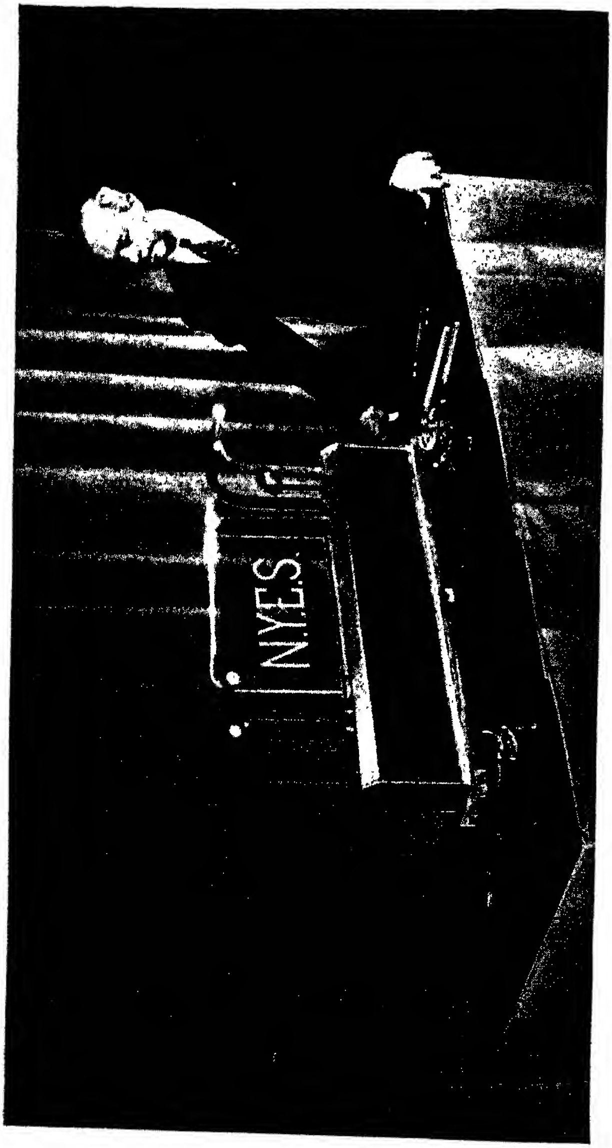


FIGURE 52. Edge-lighting is another property of Lucite. Light from electric lamps concealed in the box travels upward through the solid curved pieces of Lucite, appearing only at the ends, edges, and where the surface has been roughened by engraving. Lucite resembles quartz in this optical behavior. (Courtesy E. I. du Pont de Nemours & Co., Inc.)

yields the attractive material used in wrapping and decorating, *cellophane*.

Our list is by no means complete, but already we see that *explosives* figure very prominently in the substances which can be made with the aid of our present assortment of raw materials. Explosives are fully as interesting to the scientist as they are to mining and civil engineers and to military experts. High explosives provide very concentrated forms of energy, useful in peace as well as in war; and they are interesting chemically as conspicuous examples of instability. In common gunpowder, the first explosive to be used, powdered charcoal and sulphur were mixed with sodium nitrate. The charcoal and sulphur are combustible; they secure necessary oxygen from the sodium nitrate (saltpeter, $NaNO_3$). The rapid combustion liberates relatively large amounts of gas in a confined space; hence high pressure results, which ejects the missile. Except that the oxygen is supplied in a separate compound, not free, this is merely a more violent action of the same sort that occurs in the cylinder of an automobile engine. In modern high explosives, however, the principal compound itself contains the oxygen. The molecules are unstable, and when a shock starts the decomposition, an action which may be regarded as internal combustion within the molecule occurs.

The formulae of the high explosives mentioned above suggest what happens. *TNT* has the composition $C_7H_5N_3O_6$; *picric acid* $C_6H_3N_3O_7$; *guncotton* $C_6H_7N_3O_{11}$; and, to include a fourth explosive made by treating glycerine, the soap-manufacturer's by-product, with a mixture of nitric and sulphuric acids, *nitroglycerine* has the formula $C_3H_5N_3O_9$. In this last molecule, for example, we see that to turn the three carbon atoms into carbon dioxide (CO_2) would require six of the nine atoms of oxygen present in the molecule; and the three oxygen atoms left over

would convert six atoms of hydrogen into water, H_2O. Actually, there are only five atoms of hydrogen present, hence the supply of oxygen is more than sufficient for a decomposition yielding the gases carbon dioxide, water vapor, and nitrogen. The reader of recent war history will encounter many names of explosives; but actually these four are the principal ones used in modern war. Picric acid is called dunnite in the United States, lyddite in Great Britain, mélinite in France, pertite in Italy, schimosite in Japan. The shells contain high explosive which is detonated when the shell strikes, scattering fragments of metal far and wide; but for the propulsive agent to eject them from the guns, less violent explosives are required to avoid disrupting the guns themselves. For this purpose guncotton is subjected to a treatment called gelatinizing, which reduces the speed, hence the violence, of its decomposition. Dynamite is nitroglycerine rendered less sensitive to shock by being mixed with sawdust or other solid filler.

On and on one could go, cataloguing the materials which creative chemistry has placed in man's hands to do with what he will. The story of dyes alone would fill a volume. No longer need the textile-maker seek out insects for cochineal; the madder roots of Europe for his red; India's plants for his blues; or Mediterranean shellfish for the Tyrian purple which once none but royalty could wear. At any cross-roads general store the humblest can buy goods colored with a variety and lasting richness that all the wealth of emperors could not buy in ancient Rome. Benzene, a coal tar derivative, yields aniline, the source of scores of dyes. The madder fields of Europe — fifty thousand acres in France alone in 1870 — have long since been put to other uses; for alizarin, the brilliant Turkey red of the textile dyer, is now synthesized from anthracene, a coal tar product. The million acres of indigo plant so arduously cultivated in India in 1880 have shrunk to a few thou-

sand, their product duplicated, and replaced, by the chemists who synthesize indigo from naphthalene.

Dyes, drugs, explosives, anaesthetics, artificial silk, lacquer for an automobile or a knob for the radio dial — creative chemistry suggests new combinations of atoms to nature, and the atoms click into place. Consider the suffering saved by the local anaesthetic novocaine, a synthetic product of fairly recent origin; or the tortures prevented since surgeons began conferring the blessing of total insensibility on their patients in the operating room by using ether, a substance which the chemist makes quite easily by treating ethyl alcohol with sulphuric acid — and how much more suffering mankind could have escaped if this material had been put to its best use from the time a chemist first discovered it, in 1544, instead of only since 1842. Materials to ease pain, to cure; materials to eat, to wear, to ride in; materials to make machines and fuel to run them; materials to build great cities of surpassing beauty or blast them out of existence — science helps us to have these in an abundance and variety so great that the problem of utilizing them for the best good of man echoes and re-echoes in the legislatures of the world.

Chapter 14

COMMUNICATION

THOSE who have seen the screen version of Marc Connelly's folk-drama, *The Green Pastures,* may recall the scene in which the character representing God, while on a tour of inspection to find out how His terrestrial project was getting along, asked a stand of daisies how they were faring. The flowers spoke up promptly to assure their Maker that they were "doing O.K." Even if they had not answered with audible sound, they might still have been conceived as communicating by another kind of wave motion; namely, light. Semaphores, signal flares, lighthouses, fog horns, musical instruments, the telegraph, telephones, radio and television are only part of the story of communication. Indeed, it does not require a great stretch of the imagination to picture our whole environment as being in communication with us. We look at a person, he smiles or gestures — and in so doing is communicating with us by means of light. He speaks, and thus utilizes sound waves to transmit what he had in mind. Just as heat, ultra-violet light or a suitable chemical bath applied to an apparently blank sheet of paper may bring out a hitherto invisible message written in sympathetic ink, so visible light, reflected by the landscape, provides the principal means for that one-sided sort of communication known to the poets as communing with nature. Light falling on the Mona Lisa and modified by it in a selective process of reflection brings out what was in Leonardo da Vinci's mind when he painted that superb masterpiece. Viewing the screen in a motion picture theater, we experience the results of a communication across time and space which, by an extraordinarily complex process utilizing

light, sound, chemical action and electricity, conveys to us what happened one time in a distant studio and what was thought by the author before the happenings took place.

Adopting this broad view of communication, we find the contents of the present chapter laid out for us—the eye and the ear, and what gets into them, and the role played by electricity in conveying ideas. In studying the man-made modifications of our physical environment, we have thus far dealt with the materials out of which things are made, and with the sources of energy at whose expense the work of manipulating, transforming and controlling matter is done. An appreciable portion of the world's work consists in transporting materials. Now we are turning to the transportation of something else that helps to modify our environment—the transportation of ideas. What we see and hear in large measure determines our desires, our habits, our outlook on life; hence the means by which we see and hear, whether at close range or across the great distances that science now spans for us, are intimately related to the course of civilization.

Sensitivity of the Normal Human Eye

The eye is one of the most sensitive detectors of radiant energy known. In perfectly empty space (no atmosphere) it could detect signals given with a candle thirteen miles away. In that case an eight-millimeter pupil (the maximum diameter of the light-admitting opening of the eye) would be receiving energy at the rate of approximately 10^{-15} watt, or 0.000000000000001 watt. This is about the rate at which the naked eye receives energy from a sixth magnitude star, the faintest perceptible without optical aid. If a protected gram of water stored up energy at that rate continuously without loss or interruption, its temperature would rise

one degree centigrade in 1,340,000 centuries! This gives a good idea of the normal eye's maximum sensitivity.

The eye possesses two remarkable properties of adjustment. Disregarding, for the moment, its power of *accommodation* for clear vision at different distances, let us consider *adaptation,* the eye's ability to change its sensitivity according to the illumination. Adaptation is studied by measuring what is known as the contrast sensitivity. This is the least percentage by which the brightness of the field of view must be increased if it is to appear detectably brighter. Field brightness is expressed in terms of the number of standard candles to which each square centimeter of the field is equivalent. In these units, the brightness of a heavily overcast sky on a very dark day may be about 0.004, that of the moon at its brightest 0.25. Over that whole range of brightness, and indeed over the larger range from 0.0001 to 10 candles per square centimeter, the contrast sensitivity of the eye remains nearly constant at a value of about 2%. Thus at a brightness of 0.0001, the least detectable increase is 0.000002; but if the original brightness is 10, the increase must be at least 0.2 to be discerned. Hence, in round numbers, the eye is 100,000 *times* as sensitive at the weaker of those two brightnesses as at the stronger!

Part of this change of sensitivity is due to variations in the size of the pupillary opening, but only a small part, as we can see by a simple calculation. The pupillary diameters in this example will be about 2.0 and 5.5 mm., respectively, and the light-gathering *areas* will be to one another as $(5.5/2.0)^2$, or 7.6 to 1. Thus, if the opening or narrowing of the pupil were the eye's sole means of adjusting its sensitivity, the sensitivity at the weaker of those two brightnesses would be only 7.6 times the other. Actually, it was 100,000 times; hence some other factor must have accounted for a change of 100,000 divided by 7.6, or 13,000-fold. *That other*

factor is the change of sensitivity of the retina of the eye, which receives the image formed by the eye-lens. This enormous change of retinal sensitivity is known to be related to a chemical substance called the visual purple, which circulates in and around the rods and cones of the retina in greater or less abundance as the brightness of the field of view changes. Since the eye can thus vary its sensitivity by many thousand-fold, one can readily imagine the effect of looking alternately at dim and bright fields of view. The change of sensitivity does not occur instantly, hence an eye which has rendered itself highly sensitive in an effort to read dimly lighted print is being shamefully mistreated if allowed to rest occasionally on a very bright lamp.

Illumination

This obvious conclusion immediately raises the question of suitable indoor illumination. We see objects by light that comes from them to our eyes. They may emit the light themselves, as in the case of lamps, suns, fireflies, certain fish, or fluorescent screens excited to luminescence by x-rays or ultra-violet light. Most of the objects that we see, however, are not self-luminous, and merely reflect to us a greater or smaller fraction of the light that falls on them.

Reflection is of two kinds, specular and diffuse. *Specular* reflection is observed at mirrors and other very smooth surfaces. It enables such surfaces to form images, makes them appear shiny. Reflection of this type does not reveal the reflecting surface. Instead, it shows what the light came from before striking the surface; for example, a lamp bulb, or your face. A perfect mirror would therefore be invisible. Only the light that is *diffusely* reflected, as by the rough granular surfaces of walls or human faces,

helps us to see the details of the objects themselves. Riding behind the headlights through the rain on a smooth wet street at night, one notices how nearly useless the beams are for the purpose of showing the street's surface. The concentrated beams are reflected on ahead by the smooth wet surface, possibly into the eyes of an approaching motorist; and very little light is diffusely reflected to relieve the inky blackness of the street.

When the light in question is white, or nearly white, we often disregard its *quality,* which is to say the different colors or wave lengths included in it, and content ourselves by specifying what is called the *illumination.* This is usually expressed in arbitrary units called *foot-candles.* Do not confuse illumination with brightness. All parts of this page are probably equally *illuminated,* but obviously the inked portions are not as *bright* as the uninked. A sheet of paper held 1 foot from a standard candle receives an illumination of 1 foot-candle. Good modern incandescent lamps give nearly a candle-power per watt. Thus a 100-watt lamp, if operated at the correct voltage, is a source of about 100 candle-power, and at a distance of 1 foot from such a source the illumination would be 100 foot-candles. At 2 feet, the illumination would be much less; since the light, traveling outwards in straight lines from the lamp, spreads out both horizontally and vertically and thus is rapidly distributed over a wide area. The same beam of light that would be completely intercepted by a screen 1 square foot in area held 1 foot away, would, at twice that distance, be spread over an area both twice as wide and twice as high, or four times the area of the original screen. Thus the amount of light falling on each square foot, on which the illumination depends, is now only ¼ of the original quantity. If we take two pint cans of white paint, spread one thickly over a small area, the other thinly over a large area, there will evidently be less paint per unit

area in the second case. Just so in our problem of illumination. Doubling the distance from the source of light quadruples the area over which a given amount of light is spread and so reduces the illumination to one-fourth its original value; tripling the distance reduces the illumination to one-ninth; etc. The illumination is *inversely* proportional to the *square* of the distance from a small source of light. This explains why bringing one's book only a little closer to a reading lamp increases the illumination on the page so noticeably. (Of course, concentrated beams from searchlights do not spread out as supposed above, and so do not obey the inverse-square law.)

Artificial illumination may be direct, or indirect. If the former, light from the lamp falls directly upon the objects to be viewed. In indirect lighting, the lamps are concealed, and illuminate the room by diffuse reflection from the walls. Indirect lighting, although the original cost of installation is slightly greater, and the monthly electric bills somewhat larger (due to losses of light by absorption at the walls) is far better for the eyes than direct lighting, and also improves appearances by substituting widely diffused beams for the concentrated shadow-casting beams of direct sources. From a purely financial standpoint, the cheapest method of lighting a room would be to use one single powerful unshaded globe in the center of the room. Aside from the continual discomfort of living in homes lighted in that way, we know now that the cost of the oculist's services occasioned by the resulting eye-strain usually more than offsets the slight extra cost of using indirect lighting, or at least substituting a number of well-shaded lamps for the single intense source. The light should fall on the object to be viewed, not directly into the viewer's eyes. One still finds many buildings illuminated with a grotesque disregard of the most elementary considerations of eyesight preservation. Use of a

single strong central lamp really presupposes that all the occupants will sit facing the walls!

Remember, also, our data on the eye's power of adaptation. When focused on dimly illuminated print, it adjusts its sensitivity to a value which may be *several hundred, possibly several thousand times* the sensitivity it has when very bright objects are being viewed. Contemplate, then, the effect of lifting the eyes from a poorly lighted page to encounter a brilliant lamp. The eye cannot protect itself *instantly* by reducing its sensitivity, and it cannot instantly go back into high, so to speak, on returning to the page. The medical x-ray specialist allows 5 to 10 minutes in the dark room to sensitize his eyes for a fluoroscopic examination. If eye-comfort and appearance of the room were alone to be considered, the best lighting would result from rendering large areas of ceiling and walls feebly self-luminous, to shed a faint glow which nowhere would appear bright yet by its aggregate effect would provide ample illumination, an indoor substitute for sky-light. But several moderately strong sources well distributed, and suitably shaded, give a satisfactory compromise.

The Photoelectric Photometer

The emission of electrons by light-sensitive materials is now used in making lighting surveys. The older forms of photoelectric cells, in which a plate of light-sensitive material, often a caesium, potassium or sodium compound, was placed opposite an electron-collecting loop of wire within a glass bulb, required a reasonably high positive voltage on the loop to attract the electrons emitted by the plate. Recently this inconvenience has been eliminated by the development of the so-called barrier-layer photoelectric cells, of which the Photronic cell made by the Weston Electric Company is an excellent example. Such a cell acts as a

miniature power plant, producing a current when illuminated, and requiring no external source of voltage. The only accessory needed is a sensitive ammeter, or rather, microammeter — for under ordinary illuminations the current is only a few millionths of an ampere. But suitable portable microammeters are available, so that now for the first time the home or factory finds a handy and accurate means of eliminating the guesswork which heretofore has so largely reigned in this field. One can calibrate the instrument in a photometric dark room, using a standard lamp and the inverse-square law, or can buy one already calibrated in foot-candles. These handy "electric eyes" are now being used in great numbers, and their ready availability removes one of the last excuses for the deplorable lighting conditions under which the past generation, in the main, grew up. An illumination of from 10 to 20 foot-candles is considered satisfactory for close work at the desk.

Also, by letting these artificial eyes look at suitably illuminated surfaces, the reflecting powers of materials can be determined. Thus various grades of textiles and papers can be tested, the effects of dyes and paints studied. Already photoelectric cells are being used in the diagnosis of complexions for the guidance of the cosmetician, and by the time this book appears photoelectric devices of the coin-in-the-slot type may be available at public beaches to guide bathers in acquiring their sun-tan. Other uses of photoelectric cells will appear as we make our leisurely progress through matters related to communication in the broad sense in which we are using the word.

Image-Formation

In addition to adaptation, the eye also possesses the power of *accommodation*. The parts of the eye, from front to back on the

central axis, are: Cornea; Aqueous Humor (liquid); Crystalline Lens; Vitreous Humor (thin jelly); Retina. The eye accommodates for objects at different distances by changing the front curvature of the lens.

The optical action involved here is *refraction*. All rays are bent when entering a medium of different optical properties except those that strike the surface perpendicularly. It is this property of light which makes not only eyes, but cameras, telescopes, field binoculars, spectacles, and all other lens-using instruments possible. Two types of images are formed by refraction. Images on the camera film, on the motion picture screen, on the retina of the eye, are *real* images. Cones of light from different points of the object actually come to intersections on the screen to make a point-for-point reproduction of the object. In other cases of image-formation the role played by the lens or other agent is to change the direction of the rays in such a way that, without actually coming to a focus, they *seem* to come from some place other than their true source. Such images are called *virtual* images. Real images can be viewed either on a screen or, by placing the eye a suitable distance beyond the image, directly in space; but virtual images are always seen in space, never on a screen. It must be perfectly apparent to the reader that any viewing instrument which in use is held close to the eye is forming a virtual image; for, if the rays came to a real focus, that real focus would lie beyond the exit eyepiece, and the observer would have to back his eye away at least the distance of distinct vision from the real image in order to see it. The distance of most distinct vision averages about 10 inches.

One of the commonest examples of the formation of virtual images is the apparent elevation of the bottom of a pool of clear water. The bottom is seen by means of rays which come from it through the water's surface to the eye. On leaving the water they

bend outwards, away from the perpendicular, as shown in the diagram; with the result that a small bundle or cone of rays which actually came from the bottom now seems to be spreading out from a point above the bottom. The observer, doing what he does all his life, unconsciously traces those rays back along straight lines and thus sees the bottom of the pool above its actual location. On stepping in, he finds his legs wet much higher than appearances suggested. To illustrate this, watch this type jump upwards towards the eye when a block of thick plate glass is slid over it. We are so used to the fact that light travels in straight lines in a continuous medium that we make no allowances for bending, and thus always see an object at the point from which the light seems to be spreading when it strikes our eyes. Thus the optical illusions known as virtual images are formed. The same sort of effect can be produced by mirrors, as is also illustrated in our plate of diagrams. The reader should remember that light actually consists of trains of excessively tiny waves; and the rays used in our explanation are really imaginary lines showing the directions in which the waves of light are progressing.

Accommodation and Focusing

The normal eye automatically adjusts itself for objects at different distances. In this respect, it may be looked on as a self-focusing camera. Whether in camera, eye, or motion picture theater, the light must come to an intersection upon the appropriate screen if a clear sharp image is to be formed. The lens of the eye resembles that of a camera in one respect. Both are convex, thicker at the middle than at the edges, and so converge light from distant sources to form real images. The bending of the light by the lens causes a bundle of rays that came from the top of

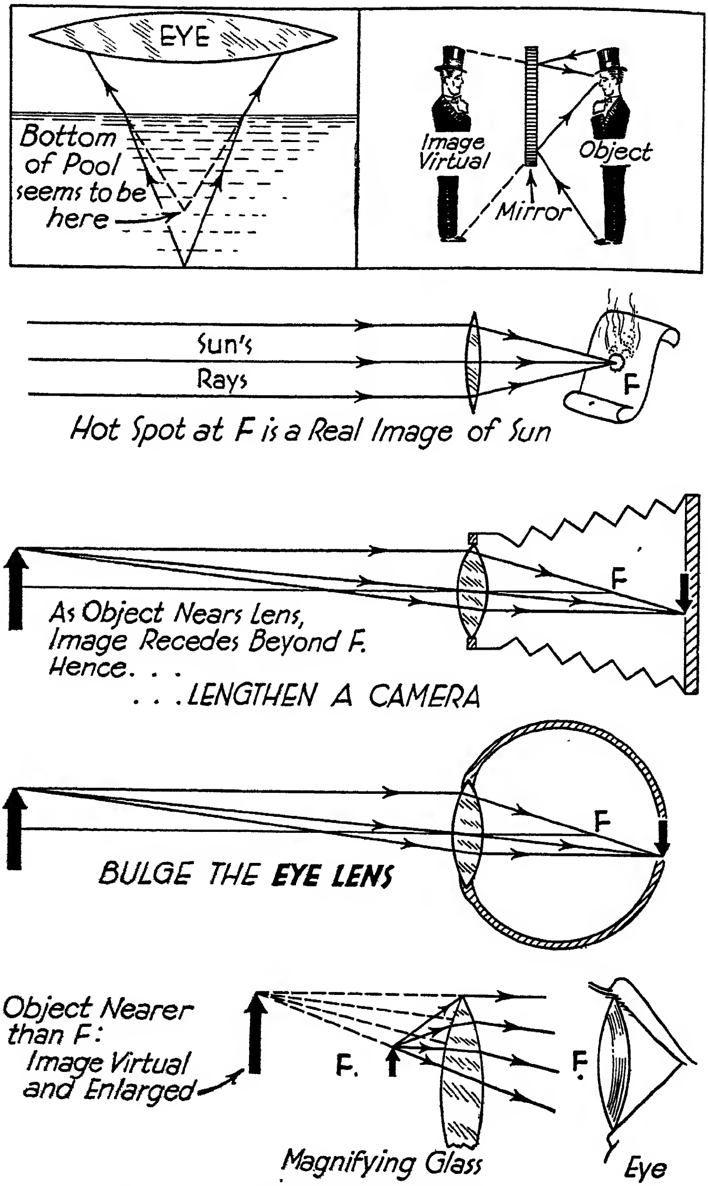


FIGURE 53. Images may be either real or virtual.

the object to intersect at the bottom of the image; hence inverted images are formed, as everyone who has used ground-glass focusing in camera work well knows. The reason we do not *see* objects upside down is that we unconsciously correct for the inversion. In some interesting psychological experiments several years ago, human subjects wore optical harnesses attached to their heads, so that what the eye looked at was an image, already inverted, of the surroundings. The lens of the eye re-inverted the image, so that during the first few days everything seemed to be upside down though the images on the retina of the eye were actually erect. However — and here was the point at issue — the subjects were soon correcting unconsciously for this extra inversion, and were seeing objects right-side up again. What would happen when the inverting harness was given up was naturally a subject of some suspense. Would the subjects recondition themselves to the normal situation? Or would they go through life seeing a world oriented as the images actually are on the retina of the eye; namely, upside down? Fortunately for the subjects, they unlearned about as readily as they had learned.

When the object is very distant, say a mile or more, the real image formed by a convex lens is as close to the lens as it can be. This particular image-distance is called the *focal length* of the lens. As the object comes closer, the image recedes, and grows larger. Note how large the image is in the movie theater, where the full length of the hall is purposely used to ensure a great image-distance and therefore a large image. As the object continues to approach the lens, the image recedes until it becomes, as we say, infinitely far away when the object's distance from the lens equals the latter's focal length. This really means that the rays emerge parallel. Then, if the object comes closer still, the image comes back on the other side of infinity, so to speak, and we have the

enlarged erect *virtual* image familiar to persons who use magnifying glasses to read small print.

Since the image-distance depends on the object-distance, adjustment is necessary to gain the best results. In the larger cameras, the length of the camera can be changed. In non-adjustable cameras the length is fixed by the maker at the correct value for a useful average distance of object, and the user hopes for the best. Such cameras are invariably short to minimize the effect of lack of adjustability. And what of the eye? It is perfectly possible to imagine a race of beings whose eyes focus as does a camera, by changing the distance between lens and screen (retina). The lenses of such eyes would be retracted on viewing distant objects, and would shoot forward to focus on one near at hand. The unfortunate members of such a race might well use bumpers of some sort to guard their projecting eyes. In the actual human eye, the distance between lens and retina remains constant at about 1 inch, and the *shape* of the lens changes. The lens is nearest to flat when viewing a distant scene. As the object approaches, the image tends to recede beyond the retina; but the eye-lens bulges and thus, by bending the light rays more sharply, brings them to a focus on the retina. Far-sighted persons evidently need convex spectacles, to make up for the eye's inability to render its lens sufficiently convex to focus near objects; and near-sighted persons need concave spectacles to offset the undue convexity which the eye-lens retains when viewing distant scenes.

By studying the paths of rays through a lens, as illustrated, the reader may use his knowledge of similar triangles to prove an important relationship: *the lengths of image and object are to each other as their distances from the lens.* In the human eye, the image-distance is about 1 inch. If the object viewed is 25 feet away, the image-distance is approximately 1/300 that of the object,

and the length of the image is therefore 1/300 that of the object. If the object viewed is a 6-foot man, the image on the retina is about ¼ inch high from head to toe; yet within that tiny image the observer readily detect's the man's eye, whose image will be about 0.0035 inch in diameter. One can infer from this the fineness of structure of the retina and its nerve-system.

The simple law of image sizes can easily be applied by the reader to other illustrations, such as motion picture projection, portrait work, photographic enlarging. By measuring the size and distance of the sun's image, as formed by a good convex lens, and knowing the distance to the sun, one can make a rough determination of the sun's actual size. The same law holds for virtual images. Thus, if a simple magnifying glass forms a virtual image at the distance of most distinct vision (about 10 inches) when the object being viewed is 1 inch from the lens, the image will be about 10 times as long as the object, and 10 times as wide. The effect of the magnifying glass here is to make the object appear as large as it would if it could be distinctly seen when only 1 inch from the eye. In dealing with the apparent sizes of objects and images, we usually express results in terms of angle subtended at the eye. In the astronomical telescope, for example, the objective lens forms a small, real, inverted image of a distant object close to the eyepiece, and the eyepiece, using that image as its object, forms an enlarged virtual image of it. The final image appears larger than the object because it is so much closer to the eye that it subtends at the eye a much wider angle. Incidentally, since this final virtual image is erect with respect to *its* object, but that object is itself an inverted image, the final image formed by an astronomical telescope is inverted with respect to the distant object. Manufacturers sometimes receive telescopes returned by amateurs with the complaint that they show things upside down.

The inversion is a natural result of the optical action, but may be remedied by adding extra lenses to re-invert the image. Both erectness and magnification are important for terrestrial work; but the magnification should not outrun the light-gathering capacity of the objective lenses. An 8-power prism binocular, for example, needs objective lenses about 30 millimeters in diameter if bright images are desired

Persistence of Vision

In addition to accommodation and adaptation, the eye possesses a third remarkable property, one which makes possible the most widely patronized of all the arts: the motion picture. This property is *persistence of vision.* Although the image, in an optical sense, ceases to exist the instant light ceases to reach the retina, the effect of that image persists for an appreciable fraction of a second. If a second image is formed before the effect of the first has disappeared, the result is what seems to be a smooth transition from one image to the next. This power of the eye was utilized by Sir Isaac Newton in his classic experiment with the color disk, in which a disk bearing several segments colored red, blue, green, etc., was made to appear white by means of rapid rotation. If images follow one another at the rate of 16 per second or faster, the rapidity of succession is sufficiently above the flicker limit to produce apparent continuity. In silent motion pictures, 16 instantaneous snapshots of a moving scene were made every second, and flashed on the screen at the same rate. Thus the illusion of motion was produced. In sound pictures, 24 per second is preferred for acoustical reasons. The illusion of abnormally slow motion, or abnormally rapid, is readily obtained by taking the snapshots at one frequency and projecting them at another.

If a photoelectric cell connected to a sound amplifier be focused on an apparently steady bright background of a movie scene, the pitch of the resulting groan in the loud-speaker will reveal not only the intermittency of the illumination on the screen, but also the frequency of the alternations from light to dark. Photographing one motion picture to serve as background for a scene of another, to save the expense of transporting players to the desired locale, presents a nice problem of synchronization. The camera taking the picture must operate exactly in step with the projector which is furnishing the background. A similar problem of synchronization has presented difficulties in television.

Closely related to the illusion of motion is the *stroboscopic* effect. Here, by illuminating a rotating machine with a single intermittent source of light, and timing the successive flashes to bring them exactly into step with the rotation of the moving part, say a flywheel, the moving member can be made to appear to stand still. It can be seen only when illuminated, and if it is always in the same position when illuminated it will, as a result of persistence of vision, seem to be stationary. The advantage gained by this method of observation must be obvious; for the centrifugal distortion, loosening of the wires of a dynamo, or other effects of high speed can be studied with ease, merely by looking at the machine. A source of light possessing very little lag is required for stroboscopic work. Incandescent lamps, whose light is a relatively feeble by-product of heat, are not suitable, since the filament does not cool off appreciably during the alternations of the electric current. In modern neon glow lamps, however, light is produced very efficiently, not by heating a metal wire, but by discharging electricity through rarefied gas. This effect is nearly instantaneous, and therefore well adapted to stroboscopic requirements. If the frequency of illumination is varied, the rapidly moving part

can be made to appear to go either forward or backward at any desired fraction of its actual speed. The reader with a liking for figuring may enjoy specifying the exact conditions of illumination required to make a flywheel appear to rotate backwards at one-tenth of its actual forward speed; or—an analogous problem—what relations must be satisfied if a spoked automobile wheel is to appear to spin backwards at a certain speed on the motion picture screen.

Quality of Illumination: Color

One property which the eye does *not* possess is that of analyzing light. Heretofore we have dealt with arbitrary units called foot-candles, and thus tacitly ignored the quality, or color, of the illumination. Color is a fascinating, important, and difficult field of study. The language of physics enables one to inform another what color he is referring to without sending a sample or using a code; but the scientific curves and figures describing the color are meaningless to the uninitiated and indeed convey no immediate mental picture of the color to the physicist himself, except in the simpler cases. But they do permit the color to be reproduced exactly. Complicated and expensive methods of spectrophotometry are needed if the quality as well as the quantity of the illumination is to be analyzed and prescribed with the precision of chemical analysis.

Hence our clumsy attempts to deal with color in daily life. Try to get a color-match over the telephone! Witness the confusion of color cards, color numbers, and arbitrary color names manufactured out of whole cloth for use in trade. The difficulties are inherent in the nature of light and in the functioning of the human eye. Visible light is, as we have seen, a motion produced

by atomic and subatomic vibrations. The quality of a vibratory disturbance can be expressed in terms of either the frequency of the vibrations or the wave length of the resulting radiation. In sound, the frequencies are relatively small, a few tens or hundreds or thousands of vibrations per second, and these are used to specify the pitch. In visible light, the frequencies are very great, reaching nearly a million billion vibrations per second in the extreme visible violet, and it is customary to use the wave length, instead, to describe the quality. From the extreme visible violet to the extreme visible red the wave lengths range from 400×10^{-7} to 800×10^{-7} cm., or, using units of exactly the right size to permit us to drop the inconvenient 10^{-7}, from 400 to 800 millimicrons, written mμ. A millimicron is thus one ten-millionth of a centimeter. These wave lengths, small as they are, can be measured so precisely that the standard meter has been redefined in terms of the number of waves of a certain green light that must be laid end to end to make 1 meter. If the standard meter bar now reposing in the archives of Paris were to be lost or destroyed, it would quickly be duplicated by means of measured light waves.

As an example of the use of wave lengths, the brilliant orange color of the light obtained by throwing some table salt (sodium chloride) into a flame is specified by its wave length, 589 mμ. It must be granted, however, that only long practice will cause this number to arouse in the mind the same vividness of idea that is conveyed by the word *orange*. Indeed, the physicist finds no sharp divisions in the spectrum, merely a gradual increase of wave length as one goes from the violet to the red end of the spectrum. To the physicist, radiations of wave lengths 489 and 689 are merely 100 units shorter, and 100 units longer, respectively, than the sodium light mentioned above; but to the eye, the change is also one of kind, from the original orange to blue at the lower

value, red at the upper. Since color as a sensation is thus primarily a psychological matter, the physicist does not deal with it. He measures what gets into the eye, and the sensations that result are for the psychologist to deal with. But obviously, a knowledge of the true physical nature of the stimulus must be the first step towards an understanding of the sensations.

Since observers differ psychologically, writers differ regarding the wave length limits of the color regions of the spectrum. These may be stated approximately as follows: *Violet,* 400–446; *Indigo,* 447–464; *Blue,* 465–496; *Green,* 497–557; *Yellow,* 558–588; *Orange,* 589–634; *Red,* 635–800 $m\mu$. Many observers cannot see as far into the violet or the red as the limits 400 and 800 indicate. Beyond these limits the spectrum extends continuously in both directions without presenting any fundamental difference from the radiations which fall within the eye's very narrow range of response. To a hypothetical race attuned to a different region of the whole long spectrum, the world would doubtless present a very different appearance. The discovery that homing pigeons find themselves seriously handicapped in the vicinity of powerful radio stations suggests that our speculation on senses somewhat different from ours is at least not fantastic.

A monochromatic (one-colored) illumination is completely described when one specifies the wave length of the light and the rate at which it transfers energy. Most illuminations, however, are composite, and to describe them exactly one needs to specify all the wave lengths included, also the distribution of the total energy among those wave lengths. Thus the problem becomes very complicated. Furthermore, only psychological data reveal what sensation the composite beam will produce. For example, if illuminations consisting of 100 energy units of wave length 500 (blue-green) and 31 units of 620 (orange-red) are simultane-

ously superimposed on one half of a white disk, and the adjacent half illuminated with 12.6 units of 450 (indigo-blue) and 48 units of 550 (green-yellow), the two halves will match for the normal eye. The two illuminations are by no means the same physically, yet they are equivalent psychologically. There is no interaction between the different wave lengths; the apparent blending must occur at the retina or in the nerves or brain. A spectroscope will quickly sort out the wave lengths included in the beams, but the eye does not.

Colors of Objects

The colors of objects depend both on the materials and on the composition of the light that falls on them. The white light of an incandescent lamp contains all the colors, giving a continuous spectrum when analyzed with a spectroscope. If this light falls on a piece of white paper, the paper appears white, showing that it reflects all the colors. But under the same illumination a piece of cloth may appear red, blue, or any other color. Obviously the colored cloth reflects only part of the light that strikes it, absorbing the remainder. Thus colors by reflected light are understood. By illuminating the sample with monochromatic light, one pure color after another, and measuring the fraction of the light reflected in each case, a complete understanding of the appearance of the cloth or other object can be reached. A piece of cloth which appears dark red in white light may appear black in blue illumination, showing that it does not reflect blue.

An instructive experiment can be performed with very simple equipment. Secure samples of every solid color of cloth obtainable, as many as 20 or 30. Secure also some pieces of colored glass, as many different colors as you can find. The Corning Glass

Works supplies many excellent glass color filters at reasonable prices. After mounting the colored samples on a sheet of cardboard and numbering them conspicuously, illuminate the display successively with light from an incandescent lamp or arc filtered through the pieces of colored glass. Record the groups that match under different illuminations. As many as half a dozen samples whose colors contrast strongly in white light may match perfectly under a certain illumination. One readily infers from this how the illusion of change of costume can be produced on the stage by merely changing the lighting. Portions of the costume which are inconspicuous in one illumination may stand out vividly in another.

Another interesting experiment is to darken a lecture room and then illuminate it solely with the monochromatic orange light made by having a multitude of bunsen gas flames play over asbestos balls or cord previously soaked in a strong solution of table salt. The room now seems to be full of corpses, to judge by the lifeless hues of the faces. Cheeks may have the potential capacity of appearing pink, and lips red; but they cannot actually reflect red to the eye unless there is red in the light which falls on them. They are not self-luminous.

The differences observed in matching colors under artificial light and in sunlight are explained by the same reasoning. A good incandescent lamp appears yellow in contrast with the sun. The sun's surface temperature is about 6000 degrees absolute, that of a 100-watt tungsten lamp filament about 2740. Owing to the sun's much higher temperature, the proportion of blue to red in its radiation is much greater than in the lamp's. The wave length of maximum energy in sunlight at the earth's surface is about 500 $m\mu$, a green; but the incandescent filament at 2740 degrees radiates most strongly in wave length 1053, which is far out in

the invisible infra-red. Only about 9.9% of the lamp's radiant energy lies in the visible part of the spectrum. Since the qualities of the two illuminations differ so greatly one would hardly expect them to give the same result in color-matching tests. The so-called *daylight lamps* are housed in blue glass globes, which absorb some of the red selectively and thus bring the red and blue more nearly into the proportions found in sunlight.

Note, in passing, that since the incandescent lamp is at best a very inefficient source of light, a relatively small drop of temperature is more serious than one might suspect. If the temperature of the 100-watt lamp filament falls only 280 degrees, or 10.2%, for example, below its normal value of 2740, not only does the total radiation decrease greatly (by 35%), but the *fraction of the total radiation* that lies in the visible portion of the spectrum also decreases, from 9.9% to 6.2%—a 37% drop.

Thus the 10.2% drop of temperature of the lamp filament causes a *total decrease of luminous energy of 59%*—and even the luminous energy that does remain is not as effective, in visual value, as that same amount of luminous energy in the original radiation would have been, because a smaller fraction of it lies in the portion of the visible spectrum to which the eye is most sensitive. This example, complicated as it is, shows the importance of operating lamps at their full rated voltage. Even one large factory, or a small town, may lose thousands of dollars annually by permitting conditions which result in the voltage being a few volts below the expected value.

And let us not pass by the fact that the wave length of maximum energy in sunlight at the earth's surface is about 500 mμ without allowing ourselves one interesting speculation. The wave length to which the normal human eye is most sensitive is very close to 500, about 555 mμ—both green! Can it be that during long ages

FIGURE 54. Transparency is a relative term. The nine and a half inch thickness of Lucite through which this subject was photographed is seen to be highly transparent to visible light, whose wave-lengths range from 400 to nearly 800 milli-microns. Advance information indicates that at 350 milli-microns (ultraviolet) about 75 percent of the radiation is transmitted by a 1-inch thickness; at 302 milli-microns, about 1 percent. (Courtesy E. I. du Pont de Nemours & Co., Inc.)

of evolution man has so adapted his eye as to utilize the earth's principal light-giver to the best advantage?

We have seen that the colors of objects viewed by *reflected* light are explained by stating what colors they reflect, what colors they absorb, how nearly complete the absorption is — and by remembering that, no matter what wave lengths a material can reflect, it does not actually reflect them unless they are included in the light which falls on the object in question. The effects produced by *mixed pigments* are similarly explained. Most of the light reflected by a solution of pigment has penetrated well below the surface before being reflected, hence the action is *subtractive*, not additive as when vari-colored beams are superimposed on a white screen. If two pigments are mixed, double absorption occurs, and the reflected light is dominated by the wave lengths which *neither* pigment absorbs strongly. Gamboge yellow absorbs virtually all wave lengths except yellow and green; Prussian blue absorbs practically all but blue and green. Only green will be appreciably transmitted through the upper layers of both, hence the mixture gives green by reflected light.

The colors of partially transparent objects viewed by *transmitted* light are equally easy to understand. The light which gets through such an object consists of the light which was neither reflected at the surfaces nor absorbed during transit of the material. If there is selective absorption of certain wave lengths, the transmitted beam will be wholly or partially robbed of them, and the light that emerges to reach the eye will no longer contain the colors in the same proportions as they existed in the original beam of light. If, for example, a white lamp appears red when viewed through a certain piece of glass, gelatine or cellophane, the filter must have absorbed the blue end of the spectrum very strongly and thus left the red predominating. If another filter absorbs all

colors completely *except* blue, it appears blue in blue light, blue in white light, and black, or opaque, in monochromatic red light.

We see that *transparent* and *opaque* are purely relative terms. Transparent to what? we should ask. Experiments with red, blue, black and clear plate glass bring out the distinction nicely. If we extend our study to the invisible parts of the spectrum, further striking results will be obtained. Aluminum and wood are highly transparent to the output of the standard Coolidge x-ray tube; yet those x-rays find a quarter-inch of lead glass, which is transparent to visible light, nearly opaque. Of two pieces of glass which both seem to the eye to be completely opaque, one may transmit the invisible infra-red strongly, the other the ultra-violet. The transmission of the infra-red can be demonstrated with an electric thermocouple, or by watching the vanes of a Crookes radiometer spin around under its heating effect. Audiences can be photographed in complete darkness with the aid of the ultra-violet; or the audience, sitting there in the dark, can be turned into a roomful of apparently detached teeth, eyeballs, and finger-nails, with here and there a tooth or some fingernails apparently missing, due to the failure of artificial teeth and false fingernails to *fluoresce* under the influence of the invisible ultraviolet. Here and there a button may shine out, a woman's blouse may chance to fluoresce a gleaming white in the darkness, though perhaps blue in ordinary sunlight. If a powerful quartz mercury arc is not available, a naked carbon or iron arc housed in a light-tight iron box provided with a Corning Glass ultra-violet-transmitting filter (opaque to the visible) as a window is an excellent source of ultra-violet to use in studying the fluorescence of different materials. Here our earlier discussion of the colors of objects fails us; for the fluorescing objects become self-luminous.

Sensitivity of the Normal Ear

Turning now to the second of the human body's two principal receivers of energy in the field of communication, we consider a few facts concerning the ear, and what gets into the ear. Different as light and sound are from a physical point of view, and different as are the sensations which they produce, we find several similarities both in the physical disturbances themselves and in the performance of our receiving organs. Both light and sound are produced by vibrations, and require for their precise description a specification of both energy and either frequency or wave length; and as regards the receiving organs, they resemble each other in their almost unbelievable sensitivity and in their ability to discern differences caused by varying the frequency or wave length of the disturbance.

The normal ear falls only a little short of the eye in sensitivity. How much energy actually reaches the ear when one hears a pin drop? If the surroundings are quiet, a pin dropped from a height of one foot upon a suitable sounding board, say a taut sheet of paper, can readily be heard at a distance of some 30 feet in the open air. By the principle of conservation of energy, the sound radiated cannot exceed the work done in lifting the pin (about 0.0002 foot-pounds) and will actually be less, for some of the energy is transformed into heat. Yet consider how many people could hear that one sound! If we allow for the spread of the energy in all directions over the surface of an imaginary sphere 30 feet in radius, we find that each square inch receives less than one ten-billionth of a foot-pound of energy.

The ear, like the eye, differs widely in its sensitivity to different frequencies; but if we choose the pitch to which the normal ear is most sensitive, about 2050 vibrations per second, which is very

close to the last C but one on the standard piano keyboard, we find by careful measurements that the ear responds to an influx of sound energy at the small rate of about 5×10^{-14} watts. Comparing this with the value previously given for the eye, we see that the eye is only a few hundred times as sensitive as the ear. How small a quantity 5×10^{-14} watts is may be judged by noting that to lift the seamstress' pin of our illustration one foot into the air at that rate of consumption of energy would require nearly two centuries.

We have already learned how small the molecules of air are, and how rapid their helter-skelter motion in all directions. When no sound waves are entering the ear, this incessant tattoo of air molecules exerts equal and opposite forces on the inner and outer surfaces of the eardrum, and thus cancel out, so to speak; but the molecules of air outside the drum do not need to vibrate back and forth *as a group* through a distance as great as the diameter of one molecule in order to produce an audible sound.

Loudness

How can we endure living when our hearing is so unbelievably sensitive? In a world of light one can at least close his eyelids. How can our ears adjust themselves to a variety of loudnesses ranging from the fall of a pin to explosions which would ruin the lecturer's microphone? Even less is known about the ear's means of adjusting its sensitivity than of the eye's; but we do know that, just as in the case of the eye, the energy stimulus must increase approximately in geometrical progression (by *multiplying*) in order to increase the sensory response arithmetically (by *adding*). This fact is reflected in the choice of units in which to express loudness. When the power of the sound waves is 10 microwatts

per sq. cm., the loudness is defined to be 1 *bel.* To double the loudness we need, not twice as many microwatts, but *10 times* as many. To triple the loudness, 10 x 10, or 100 times as much power is required. Thus 1000 microwatts per sq. cm. gives a loudness of 3 bels.

That the bel is a very large unit may be judged by noting that, whereas 1 bel represents 10 microwatts *per square centimeter*, the *total* power of the sound spread all around by one person conversing averages only 10 microwatts. This is approximately one millionth of the luminous power radiated by a 100-watt lamp. Therefore a smaller unit of loudness is commonly employed: the *decibel*, which is 1/10 of a bel. The decibel is approximately the smallest *change* of loudness that the ear can detect. For every increase of 1 decibel of *loudness*, the *power* of the sound must be increased by 26%; i.e., multiplied by 1.26. This agrees with the definition of a decibel as a tenth of a bel; for a bel involves a ten-fold increase of power and 1.26 to the 10th power is 10. What this all boils down to, is this: if the background noises are faint, a fairly small increase of sound energy is detectable; but in the midst of clamor the hearing is so dulled that a much greater increase of sound energy is required. This is precisely the sort of relationship we found in our study of the eye; but whereas the *contrast sensitivity* for the eye is approximately 2% over a wide range of field brightnesses, for hearing the corresponding quantity seems to be about 26%. Thus, great as is the eye's range of adaptation to different brightnesses, the change of sensitivity found in hearing is still greater. Much work is being done on this problem; but not even the mere fact of hearing can be said to be thoroughly understood, let alone this remarkable change of sensitivity. It is only very recently that the word *decibel* has crept into non-technical literature; but so important has noise, and the pre-

vention of noise, become, that nowadays one finds newspapers and magazines giving the results of noise surveys in decibels, and referring quantitatively to the volume of applause.

The electric equipment used in sound surveys is much more complex and costly than the convenient photoelectric cells with which illumination can be studied. Dependable measurements are possible, however, and, if history is a guide, we may expect that the accurate data now being compiled will lead to a bettering of conditions, especially in offices, city streets, and in factories which are filled with the sound of whirring machinery. A busy street intersection may register about 50 decibels, which means that sounds which would be barely audible amidst quiet surroundings must be magnified in power 100,000-fold in order to be heard above the clamor of the street. This is a measure of the deafening effect of the noise. To change from a soft whisper to very loud speech involves an increase of about 60 decibels. A typewriter being rapidly operated may produce a deafening effect of 20 to 40 decibels. The explosion of the volcanic island Krakatoa in 1883 — possibly the loudest sound described in history — is estimated to have reached 190 decibels. This single sound, encircling the earth in opposite directions, and being reflected back, passed certain meteorological stations as many as seven times.

Production and Transmission of Sound

We recognize the slowing down of a piece of machinery by the gradual lowering of the pitch of the sounds which it produces. Sound is caused by the vibrations, not of atoms, but of gross objects. Anything that possesses elasticity — steel, wood, air, a taut string — can be made to vibrate. By holding a card against the teeth of a toothed disk while it is rotating, and varying the speed, one can

readily show that the more rapid the vibrations, the higher the pitch. The vibratory motion of a tuning fork can be detected with the eye or a fingernail, and it can be demonstrated at a distance with a fragment of cork hanging from a miniature fishing pole. The bit of cork bounces merrily back and forth between the prongs, or, if held against the outside, is tossed high into the air. The rate of vibration can be determined by means of stroboscopic illumination; by use of a rotating scanning disk carrying a ring of holes; by electric counting; by many means.

The vibrations must occur as rapidly as about 16 per second or faster, otherwise the individual impulses will be detected. Here we have a condition which brings to mind the flicker limit of the eye, which also is about 16 per second. This similarity suggests an interesting speculation: Have hearing and seeing something in common, back there beyond the immediate organs themselves? Perhaps the reader will delve into the literature independently, to see what psychology knows about this.

On a piano correctly tuned to American standard pitch ($A_3 =$ 440) the lowest tone has a frequency of 27.5, the highest 4186 vibrations per second. The human voice in singing ranges from about 60 for a low bass to 1300 for a high soprano. The normal ear can hear sounds as high as 20,000 vibrations per second. The upper limit varies widely, and tends to decrease with the age of the subject. Beyond this, inaudible disturbances of the same physical nature as sound have been produced at five million vibrations a second, which is higher than the frequencies of the electric waves used in the common broadcast band. These supersonic waves have been used to destroy certain bacteria and insects, and, in beams concentrated by reflectors, are employed in under-water communication between ships.

The importance of air in the transmission of sound can easily

be established by the bell-in-a-vacuum experiment. The eye sees the bell ringing away vigorously under the glass jar while the air is being withdrawn, but the sound soon becomes nearly inaudible. If it were not for traces of air remaining, and for some conduction of sound through the electric wires and the sound-deadening support of the bell, no sound would emerge. The moon, lacking an atmosphere, is necessarily a completely quiet place.

By what means does the air link our ears to the vibrating body? *The air is alternately compressed and rarefied.* How can the prong of a tuning fork squeeze air which is not confined? The speed of the vibrations gives the answer. Suspend a sheet of paper by one corner, and push slowly against it with a pencil point. The whole sheet moves away. Now strike the paper sharply. The pencil point punctures the paper. The *inertia* of the paper supplies the backstop, bringing a strong reaction into play if we attempt a rapid acceleration. Just so with the air. The vibrating prong pushes so quickly that before the air can flow away in all directions, it is squeezed as a result of its own inertia. This air squeezes the next, and so on, until at length the air outside the ear-drum is compressed. Meanwhile, the prong has receded, tending to open up a hole in space; but air rushes in to fill the space, reducing the pressure beyond it, and soon the molecules of air next the ear-drum are moving outwards. So it goes. Air molecules are made to vibrate in step with the vibrating source of sound, and *they* cause the ear-drum to vibrate. By photographing the air with the aid of instantaneous flashes produced by electric sparks, we can record the positions of the successive regions of compression and thus study the progress of the *compressional wave*. The distance from one point of maximum compression to the next is the *wave length* of the sound. In air at zero degrees centigrade, the sound waves produced by the standard A referred to above (440 vibrations per second) are 2.5 feet long.

Precisely how these air waves produce hearing is not understood. The *outer ear*, with its sound-collecting lobe and its short, narrow canal floored by the ear-drum, presents no difficult problems. In the *middle ear* one finds a system of three small bones — hammer, anvil and stirrup — linked both together and to the ear-drum. This region is connected to the outer air (by way of the upper throat) by the Eustachian tube. The *inner ear*, known as the bony labyrinth, contains fluid and houses the nerve terminals, also the semicircular canals, our organs of balancing. The system of bones in the middle ear possesses a certain amount of leverage, which, according to some writers, amplifies the feeble forces exerted by the vibrating ear-drum and transmits them to the inner fluid. But easy explanations cannot apply here. There is serious doubt whether the excessively minute quantities of energy to which the ear can respond could be transmitted by the motion of relatively heavy levers as a whole. Successful reception of sound by bone conduction directly through the skull, without benefit of the ear-drum, raises unanswered questions. Not the least of the problems on which further light is needed is the ear's ability to distinguish different pitches amidst a medley of sounds. Here the ear surpasses the eye. Pitch in sound corresponds to color in light, and several wave lengths of light, reaching the eye simultaneously, are not separately detected, but blend together. Dr. Harvey Fletcher's book, *Speech and Hearing*, will be found excellent reading. Much is known, but many problems await solution.

Localization and Sound Ranging

Since masses of matter are involved, sound is slow in comparison with light. In air at zero degrees centigrade, the speed of sound is 1087.5 feet per second. The speed increases as the temperature rises, but is independent of *pitch*. Suppose the contrary were true,

and sounds of different pitches traveled at different rates? Composers would need to arrange their music to be heard at a given distance, and persons seated at other distances would not hear the notes in the desired order. Fortunately, all sounds travel at the same rate in air. Allowing a fifth of a mile per second gives satisfactory results for quick estimates. Light travels nearly a million times as fast as that, so in many problems may be considered to take no time at all. If the lightning is seen 3 seconds before the thunder is heard, the discharge occurred about $3/5$ of a mile away.

The fact that our ears number two, not one, is partly responsible for our ability to sense the approximate direction from which a sound comes. In general, the two ears will not be at the same distance from the source, hence the maximum compressions of air outside the two ear-drums will not occur simultaneously. The sounds at the two ears will be out of step. This *difference of phase* disappears when the sounding object is directly ahead, or directly behind. The matter is not fully understood, but there is no doubt that a difference of phase at the ears is an important factor. Experiments in which the phase difference is artificially varied deceive a blindfolded subject completely: he thinks a sounding body is moving all over the room. If our ears were farther apart, localization should be easier. In locating submarines or airplanes, a pair of sound collectors is sometimes used — funnels in air, hollow rubber bulbs for under-water work. These are mounted at a convenient distance from each other, and the whole apparatus rotated until the phase difference at the ends of the connecting tubes disappears. The object sought is then in a direction at right angles to the line joining the sound collectors. Whether it is before or behind, can be judged by the intensity of the sound.

In the World War, projectiles were heard screaming through the air overhead before the sound of the explosions that sent them

forth reached the trenches. Further, by timing the sound of the explosion at three listening posts, sound engineers quickly located concealed artillery. If the sound reached listening posts B and C one and two seconds later, respectively, than it was heard at A, then the gun in question was about one, and two, fifths of a mile farther from B and C, respectively, than it was from A. Drawing circles of these radii around B and C on the map, one knew that the sound must have reached A and those two circles simultaneously; hence the source lay at the center of another circle which passed through A and touched those two circles. By using automatic devices, and correcting for the effect of temperature on sound speed, the sound-ranging experts often had their own artillery dropping shells on the gun in question within a minute or two after it had emitted the telltale sound.

Solids and liquids also transmit the compressional waves of which sound consists. Sound travels more than fifteen times as fast through iron, and more than four times as fast in sea water, as in air. Automatic depth-sounding indicators have come into use in navigation. Short, sharp sounds made under water are reflected back by the ocean floor, to an electric listening device. The time required for the sound to go to the bottom and return, together with the known speed of sound in sea water, reveals the depth. Thus modern science makes the old word *sounding* come literally true. From this, it is easy to recognize the possibility of an automatic device which draws the contour of an ocean floor while the ship moves along above it.

Architectural Acoustics

The increasing use of public address amplifiers, together with the steady rise of the noise level in hotels, apartment buildings and

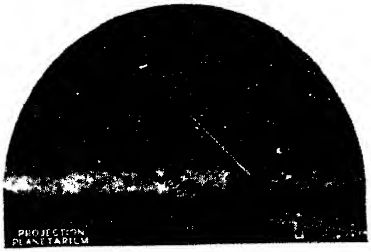
private homes as more and more radios, bathrooms, and motor-driven household appliances come into use, bring to the fore certain principles of acoustics which, though always important, have often been neglected. *How much sound will be produced? What will become of that sound?*

If sound is *not* to be produced, all possible causes of vibration should be studied. In rotating machinery, for example, the emission of sound may be reduced by lubrication, by improving the exactness with which parts fit, by rounding surfaces to reduce the agitation of the air to a minimum, by adjusting the moving parts to eliminate unbalanced centrifugal effects.

The sound that *is* produced in a room may be reflected, absorbed, or transmitted into the surroundings. Echoes remind us frequently that sound can be reflected; but it is important to remember that even when distinct echoes are not heard, reflection of sound is continually occurring. If one makes regular ripples in still water in the vicinity of a floating beam, he can see the ripples reflected by the beam. This is a good picture to have in mind when thinking of what happens when sound strikes the walls of a room.

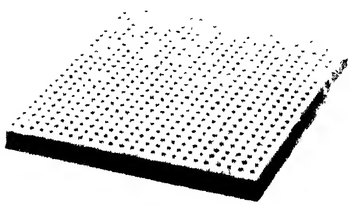
In addition to the more conspicuous acoustical defects of auditoriums — noticeable *echoes;* the *whispering gallery* effect, due to the concentration of reflected sound by the focusing action of concave portions of walls or ceiling; *silent points,* where perchance a concentrated reflected beam meets the direct beam out of phase (owing to the difference of distance traversed) and so produces partial *interference* when certain conditions are satisfied — in addition to these, the massed effect of sound reflected by all exposed surfaces produces reverberation which is undesirable if it lasts either too long or not long enough. The *reverberation* period of an auditorium is the extra time during which a sound is heard as a re-

FIGURE 55. CONTROL OF REVERBERATION



Left: A stainless steel ceiling perforated with 4608 holes per sq. ft. solved the acoustical problems presented by the hemispherical sky in the Hayden Planetarium. The holes transmit sound to a porous backing, whose pockets of trapped air absorb the energy and transform it into heat. (Drawing courtesy American Museum of Natural History, New York.)

Right: A means of reverberation control adapted to less unusual situations — an acoustical panel of pressed asbestos and cement (transite) backed by a rock wool blanket. Sound entering the holes of ceiling or wall panels is not reflected back into the room. (Courtesy Johns-Manville.)



Left: Beauty combined with acoustical control. The spaces between the beams of the Doheny Library ceiling, Los Angeles, are padded with asbestos felt faced with decorated membrane. (Courtesy Johns-Manville.)

sult of repeated reflections. The best value depends on the size of the room and on the uses to which it is put; from one to two seconds may, in general, be considered good. If so much sound-absorbing material is crowded into a room that the sound dies away almost as soon as uttered, the speaker's voice will seem weak and lacking in richness; whereas if large bare surfaces are present, so many reflections may occur before the sound subsides that it continues to be heard too long, thus preventing concentration on the succeeding sounds. In a large armory recently built in a southern capital, bare brick walls and a lofty bare ceiling face the interior. As a result, reflection is so confusing that the troops cannot drill effectively inside, as planned, because they cannot understand the commands. Persons gathered there to hear President Roosevelt's acceptance speech from a powerful radio had to go outside the building in order to understand the words. The means of ensuring a suitable reverberation period are well understood, and have been ever since the early 1900's, when Professor W. C. Sabine of Harvard published his pioneer studies in the field; and it is inexcusable to expend great sums in the construction of an enclosed gathering place without ensuring that the plans are as sound acoustically as mechanically.

The student of debating who has practised his speech in an empty auditorium knows the effect of reflection of sound by empty chairs — sound which is largely absorbed by clothing and skin when the hall is filled. A person absorbs as much sound as four square feet of open window would, and so is said to have an absorption value of four units. The open window is chosen as a basis of comparison because the opening does not reflect any sound back into the room. In this system, an empty wooden seat in an auditorium may absorb 0.1 to 0.2 units, which is only about one-fortieth to one-twentieth as much sound as an auditor sitting

there would absorb. Cushioning the seats multiplies their absorbing power by about ten. A brick or plaster wall reflects sound far better than the best silvered mirrors do light. There is only about a 3% absorption of sound at the wall; whereas it is a very superior mirror indeed which does not absorb 20% of the light that strikes it. Stringing wires across a hall — a popular fallacy — does not improve the acoustics appreciably. The absorption by the wires is negligible. A great multitude of wires might conceivably do some good *if only one pitch* were ever heard in the hall, and if all the wires were tuned to that pitch so as to absorb energy strongly by resonance, or sympathetic vibration; but those are not the conditions encountered. By dividing the volume of the room in cubic feet, by the total absorbing power of the room (expressed in units based on the open window, as stated), and multiplying the quotient by 0.05, one can find the *reverberation period* of a room in seconds. For example, 100 square feet of the wall referred to above would have an absorption value of only 3 units, since it absorbs only 3% as much sound as an open window would. The absorption coefficients can be found in the newer physics texts, or in books on architectural acoustics (Knudsen, Davis, Watson, etc.). Cement floors absorb about 1%; linoleum 3%; heavy velour 12%; specially prepared acoustic plasters and absorbers, 20 to 40%. It is not safe to jump to conclusions in this field. Merely varnishing wood reduces its absorbing power from about 6% to 3%.

If the reverberation period does not fall between one and two seconds, one can readily calculate how many square feet of a given material must be used to remedy conditions.

Closely related to this problem is that of *sound-proofing* a room. Here we are interested in the sound that is transmitted from the outside. What is needed is insulation. Massive construction and double walls, with no *rigid* connection between the two walls are

FIGURE 56. Sound-proofing a dance floor. Rigid connections must be avoided. Padded joist supports and a packing of soft, porous material minimize sound transmission. Similarly, an entire room can be sound-proofed. (Courtesy Johns-Manville.)

the principal means. A complete vacuum jacket would serve perfectly, but for obvious reasons is not practicable. Mounting a noisy electric motor on a sounding board and placing it within a double-walled box, is an instructive experiment. The inner box should rest on felt or resilient rubber several inches thick. Lining one box with sheet lead, and filling the space between the walls with mineral wool, sand, or other non-rigid material, improves the insulation. The sand or mineral wool helps to prevent the walls from vibrating. The basic principles are, that a non-rigid material does not transmit vibrations readily; that sound energy is dissipated wherever an additional surface separating two materials is encountered; and that sheer massiveness, or inertia, reduces the transmission. If the room-within-a-room construction is used, the inner room should be floated on resilient material, or specially suspended. Even a few nails joining the two walls will have serious results. Double windows, preferably of thick plate glass with several inches of dead air space between, are recommended. The reduction of sound during transit through different thicknesses is given for many materials, in decibels, in the references cited above. Overlooking small items can easily nullify elaborate plans: water pipes, for example; an unprotected transom; a few square feet of porous material. The increasing congestion of modern civilization renders sound-deadening a matter of vital concern if nerves are to be saved, and a decent privacy assured.

The Physical Basis of Music

Just as certain physical principles underlie the performance of an auditorium, so others underlie the music which may be rendered there. How are musical intervals determined? What is the difference between a noise and a musical sound? What physical

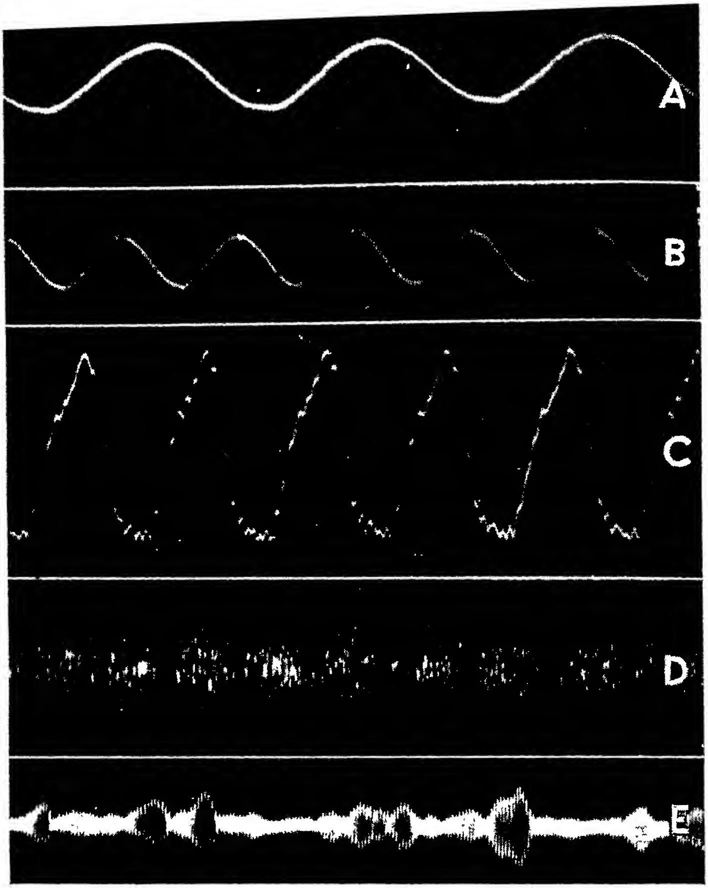


FIGURE 57. Photographic analysis of sound. A and B record the sweet but dull *pure tones* of tuning forks making 110 and 220 waves per second. The 220 is one *octave* above 110. C records the vowel Ooh sung by a vocalist trying to emulate fork B. The *pitch* (number of waves per second) matches; but the greater height shows greater *loudness*, and the shape reveals *harmonics* which render the sound more interesting. D records the *noise* of a chisel held against a grinding wheel, and E the *vibrations* of the wheel's shaft registered by contact with a piezoelectric crystal microphone. (Oscillograms in this book were made specially for it by the Acoustic Laboratory, American Steel and Wire Company, Chicago, Ill.; Dr. William Braid White, Director.)

condition must be satisfied if two sounds are to be an octave apart? What relationships govern the musical scale?

We resort to experiment. An electric motor spins a round metal disk under a set of air valves. Five rings of holes have been bored in the disk. Jets of compressed air can be directed against the disk by opening the valves. Every time a hole passes under the valve, the air beneath the disk is compressed. Thus the air is set into vibration, and sound produced.

The two inner rings contain 24 holes each, but differ in that the holes in the first are irregularly spaced; in the second, regularly. Trying them, we find that the irregularly spaced holes give a nondescript *noise,* the others a clear *musical note.* Evidently, a musical sound is one in which a regular rate of vibration is maintained. A more thorough study would show that the difference between a noise and a musical sound involves other factors as well. The vibrations may be regular and yet produce a noise-like effect if of very short duration, or of an excessively complex nature.

Now we confine our attention to the four outer rings of holes, all regularly spaced and containing, respectively, 24, 30, 36 and 48 holes. The first and last of these give notes which the ear recognizes as being exactly one *octave* apart. Since the number of vibrations per second is proportional to the number of holes, and 48 is twice 24, we conclude that doubling the frequency raises the pitch one octave. Trying all four rings, we hear the *do-mi-sol-do* series. The frequencies are to one another as 24 to 30 to 36 to 48, or dividing through by 6, as *4 to 5 to 6 to 8.* Increasing the speed of the motor raises all the pitches but does not disturb the do-mi-sol-do relationship. Therefore, *musical intervals depend on the ratio of the frequencies.*

Further tests confirm this conclusion. Substituting a card pressing against toothed wheels for our air-and-hole method of pro-

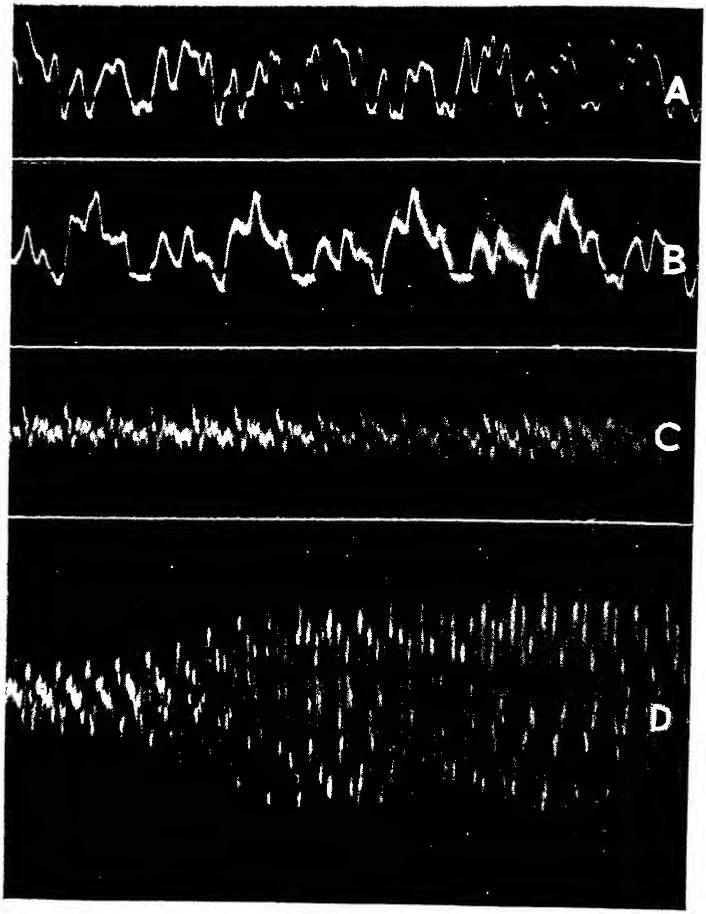


FIGURE 58. Additional sound oscillograms. Sound waves modulate the electric current in a microphone, and the current controls a tiny vibrating mirror which reflects light to a moving film. A and B show the effect of touch on a piano key. The key was pressed (A) and struck (B). The fundamental (220 vibrations per second) is the same, but the harmonics differ. C and D record a fundamental of 174.6 as sounded on a piano by Rudolph Ganz (C) and on a French horn by Fred Braid White. Note the momentary increase of loudness of the horn's note, due to an effect called sweeling. (Courtesy Acoustic Laboratory of the American Steel and Wire Company; Dr. William Braid White, Director.)

ducing sound, we find that a set of four wheels having 40, 50, 60 and 80 teeth, respectively, gives do-mi-sol-do when rotated against the card. Again the frequencies stand to one another in the ratio of 4 to 5 to 6 to 8. Four tuning forks of frequencies 256, 320, 384 and 512 yield another set of do-mi-sol-do. Dividing through by 64 gives 4–5–6–8. The proof is conclusive. The musical scale is mathematical at bottom.

One reason why the octave is so distinctive an interval can be found by studying *beats*. Try two forks of 500 and 512 vibrations per second. Separately, each fork gives a smooth sound; but together they produce an unpleasant beating effect, the loudness of the sound rising and falling twelve times a second. At one instant the two sounds are in step (in *phase*) at the ear, both compressing the air there and thus cooperating. But the 512 fork continually gains on the 500, and their waves will not be exactly in step again until the 512 gains one whole vibration on the other. Since it gains 12 vibrations every second, the two trains of waves agree in phase, and thus produce a maximum of loudness, twelve times a second. Similarly, owing to interference when the two disturbances are exactly opposite in phase, there is a minimum of intensity twelve times a second. In general, *the frequency of the beats is equal to the differences of the individual frequencies.* Test a 400 fork with the 500. The difference is 100; there are 100 beats per second; but these come too fast to be detected individually. Hence we have, in effect, a *third tone,* called the *beat tone,* which is lower than either of the two components and serves to enrich the sound. But if we try an octave, by sounding a 250 fork with the 500, the difference is 250, the beat tone has a frequency of 250, and is therefore indistinguishable from one of the original components. Whenever one frequency is twice the other, the difference equals one of the original frequencies; hence two pure notes an octave

apart do not produce a distinguishable beat tone and therefore cannot be discordant when sounded together.

When a sound-analyzing instrument, perhaps Professor D. C. Miller's phonodeik, is used to secure a photographic trace showing the wave motion which results when two sounds are combined, the wavy curve is least complex when the two sounds are an octave apart.

To round out a complete musical scale, twelve notes to an octave have been agreed upon. The musical intervals between two notes are, as we saw above, determined by the ratio of the frequencies. For the least discordance, the fractions expressing the ratios should be different in different parts of an octave, and no ratio should be smaller than 16/15, or 1.0667. In transposing from one key to another, however, it is convenient to be able to begin an octave anywhere on the keyboard; hence the interval between one note and the next has been made the same throughout the scale. The ratio used is 1.0595. This makes octaves come out correctly, at exactly 2 to 1; but sacrifices harmony elsewhere to a slight extent. The result is the equally tempered scale. Standard A is fixed at 440 vibrations per second, and the seven other A's are obtained by multiplying, or dividing, by two, until the values from 27.5 to 3520 have been established. To fill out the octave between two A's, multiply successively by 1.0595.

We have merely grazed the surface of this fascinating field, but surely even these few facts reveal the marvelous (though unconscious) *mathematical* discrimination of the trained ear.

Sound Recording and Reproduction

In addition to communication that is as nearly immediate as the speed of sound permits, there are delayed methods of communi-

cating by sound which, as everybody knows, have reached a high state of development. The printing press and ordinary cameras permit delayed communication by light; but sound presents more complicated problems. Phonographs, dictating machines and sound pictures preserve the character of the sound and permit its faithful reproduction for next week's audience or for posterity. What a treasure the Gettysburg Address in Lincoln's own voice would be if we had a record! The original venture in this field, Thomas A. Edison's phonograph of 1877, was a purely mechanical device in which the voice waves caused a diaphragm to vibrate and thus actuated a pointed stylus which cut a groove in the surface of a rotating cylinder covered with tinfoil; but today electric methods of recording have largely superseded the simpler mechanical devices of the past generation.

The student of science is interested more in the physical principles than in the details of the actual mechanism. The basic facts are, that the frequency of the vibrations determines the pitch, or quality, of the sound, and that the amplitude of the excursions is a measure of the loudness; in other words, *how fast* and *how far* the vibrating member vibrates. A long rope swing hanging from a tree has practically the same *frequency* whether the *amplitude* of its motion is great or small. If a wavy trace or similar record can be made, in which the number of fluctuations per foot of record is controlled by the frequency of the vibrations, and the magnitude of the fluctuations determined by the intensity of the sound, then the sound can subsequently be reproduced by using that trace or other record to control the vibrations of a diaphragm. By drawing a roll of paper along lengthwise under a pencil point, while the pencil steadily traces and retraces what would be a straight vertical line if the paper were stationary, one secures a wavy trace. Substitute a rotating wax cylinder or disk for the

paper, and a vibrating stylus for the pencil, and one has the simplest means of recording sound. Once the trace has been engraved, the stylus (and a taut diaphragm attached to it) can be made to reproduce the original sound merely by rotating the record under it, thus forcing it to repeat the original vibrations as it follows the wavy groove.

A single pure tone, such as the sound of a good tuning fork, gives a simple curve. A complex sound, perhaps that of a full orchestra, or a mob in a street scene, produces an amazingly complicated trace; but at any instant the numerous sound waves all add up at the recording stylus to produce a single force which controls its motion. No matter how complicated the trace is, it was made by a vibrating stylus; and if it is rerun under a stylus, the original vibrations, hence the original sound, will be reproduced. One very important requirement is, that the *natural frequency* of the recording (or reproducing) mechanism be outside the range of the pitches recorded; for otherwise, it would tend to emphasize its own pitch by resonance, or sympathetic vibration, and thus fail to give a faithful reproduction.

In *electric recording,* the magnetic effect of an electric current is utilized. The sound vibrations cause an electric current to fluctuate, and this fluctuating current, usually amplified by means of electron tubes, controls the motion of the recording device by virtue of its magnetic effect. Since amplification is added, the recording device can be less rugged, hence more sensitive, than the older mechanical devices. A *microphone* is a device for impressing the sound fluctuations upon the electric current. In the simple form used for *telephone transmitters,* an electric current flows through a chamber loosely filled with carbon granules. The voice sets the diaphragm to vibrating, and the diaphragm exerts a fluctuating pressure against the carbon. When the granules are

squeezed more tightly against one another, their contact *resistance* is decreased and a greater current flows; when the pressure is relaxed, they touch more lightly, the resistance increases, the current decreases. A carbon microphone may be looked on as a multitude of poor electric connections. It does not generate the current, merely controls it, so that the fluctuations of the current reproduce those of the sound waves. Except for telephone work, carbon microphones are gradually going out of use. More sensitive types have been developed, with great improvement in fidelity of reproduction. The condenser microphone achieves this end by utilizing sound vibrations to vary the distance between two electrified plates. A still more recent type contains a very light coil of wire which is mounted between magnets and thus generates feeble currents of electricity by *induction* when it vibrates.

Once these currents which fluctuate in unison with the sound waves are produced, they may be used either to make a sound record for future use or to produce sound immediately. By passing the current through a coil of wire which is mounted between magnets, varying magnetic forces are produced, and the coil, if suitably fastened, vibrates. These vibrations are readily transferred to a diaphragm which augments the sound. Thus the cycle — sound to electricity to magnetism, and back to sound — is complete. The vibrating coil is used in most *loud speakers*. In ordinary *telephone receivers,* two fixed coils are wound around the end of a long U-shaped permanent magnet. The fluctuating current through these coils alters the magnet's pull on a taut diaphragm, which therefore vibrates back and forth in unison with the original sound.

If a delay is desired, the voice currents must be utilized to make a record of some sort, and that record subsequently used either to produce vibrations directly, or, more commonly, to control an

electric current which in turn will actuate the loud speakers. In *motion picture* work, the sound record is usually on the film. Here, light and photochemical action appear as intermediaries in the sound-electricity-magnetism-sound sequence mentioned above. The principal optical methods are known as *variable area* and *variable density*. In the former, electric currents, after being modulated by the sound waves, move one jaw of a narrow slit by magnetic action. A steady light is shining on this slit, but the amount that gets through the slit to the moving film is controlled by the vibration of the movable jaw. The higher the pitch of the sound, the *faster* this jaw vibrates. The louder the sound, the *farther* it vibrates, hence the wider the beam of light which it admits to the film. Both quality and quantity of the sound are therefore recorded in the blackening of the film. In the theater, an auxiliary lamp shining through the sound track throws light on a photoelectric cell, thus producing fluctuating electric currents which vary in unison with the sound waves originally made in Hollywood or wherever the scene was taken. The variable density method differs very little from this. Here the brightness of the lamp shining against the slit is varied, instead of the width of the slit. A neon lamp is used, because it responds almost instantly to the fluctuations of the voice currents.

In showing a talking film, the pictures are projected in flashes, twenty-four per second, but the sound track must be illuminated constantly. These apparently conflicting requirements are met by leaving a short length of slack film between the projector and the sound track lamp. The film is pulled through the picture projector by jerks, but passes the sound track illuminant continuously.

Radio Communication

In approaching the most spectacular but one of all the methods of communication which physical science has made possible, we need to draw upon many facts previously scattered through our pages, and many more besides. Our expectations here must be modest. Telegraphy by wires, highly refined though it has been as a result of millions of dollars' worth of scientific research and engineering, is simple in comparison with radio. In ordinary *telegraphy,* the basic principle is merely that of operating a switch which, whenever it is closed, permits a small electric current to flow through connecting wires to a distant magnetizing coil wrapped around iron. The resulting magnetic force moves a small iron bar by attraction, producing an audible click if the message is to be received directly, or, more commonly, closing another switch, a *relay,* which brings into action the energy of a local source of electricity. Thus the clicks of the code are produced by local energy, which is merely *controlled* by the feeble currents flowing in the miles of connecting wires; or the local source of energy is drawn upon to relay the message automatically to more distant stations. In radio, too, the local sound is produced by local supplies of energy; but that energy is controlled by electromagnetic waves propagated without benefit of intervening wires, and the clicks of ordinary telegraphy, spaced to make the familiar dots and dashes of the code, are usually replaced by the immediately intelligible sounds of voices or musical instruments.

Recapitulating briefly, we remind ourselves of certain relevant information which has already appeared in our pages: the *vibratory nature* of sound; the *inductive effect* of alternating currents of electricity; the *magnetic effect* of any electric current; the actions of *microphones* and *loud speakers;* the *electromagnetic nature* of

light; a glimpse of the *early history* of radio — Maxwell, Hertz, Marconi; the *emission of electricity* by hot bodies, presenting the possibility of *amplification* by means of a hot-filament vacuum tube containing a controlling *grid* between the electron-emitting *filament* and the electron-receiving *plate*. Reference to the index will facilitate a review of these important matters.

So far as the production of electromagnetic waves — the carriers from broadcasting studios to homes — by alternating currents is concerned, we must accept the experimental fact that this action does occur. The mathematically exact laws of the effect are known. The waves result automatically whenever alternating currents flow in inductive circuits; but since, unlike sound, they are not propagated by ordinary *matter*, the means by which they are propagated will not be understood by anyone who insists on *mechanical* models of physical actions. The invention of the ether — something that could vibrate — was the last resort of the mechanical school of thought. The ether no longer figures in scientific discussions. Exhaustive tests to confirm its existence have all proved fruitless. The thinker who accepts the transfer of energy by induction between the primary and secondary coils of an ordinary doorbell transformer, which are not connected by wires, yet balks at a similar action when the coils are farther apart, is being as illogical as one who admits that a brick is hard to lift but will not believe that gravitation can hold the earth to the sun. Lengthening the distance may increase the practical difficulties enormously, but not the philosophical. Our problem here concerns principally what happens at the transmitting end, and at the receiver.

Just as a rope swing of a given length is naturally predisposed to oscillate at a certain rate, so electric circuits can be constructed in which the conditions favor the oscillation of electrons at a chosen

frequency. In the usual house lighting circuit, electrons oscillate back and forth with a frequency of 60 cycles per second. In the antenna circuits of stations which are broadcasting in the usual band, electrons oscillate at frequencies ranging from 550,000 to 1,500,000 cycles per second. Other frequencies are used for special purposes. A frequency of a thousand cycles per second is somewhat below the middle of the piano range, and one of a million cycles per second is somewhat above the middle of the usual broadcast band. Hence, for a rough comparison, we may think of the radio waves as having about a thousand times the frequency of the musical range. In terms of kilocycles (a thousand cycles per second) the two frequencies would be given as one kilocycle, and a thousand kilocycles. The fact that these electromagnetic waves are far above the audible range presents a problem at the receiving end; but such high frequencies are needed, for two reasons. The energy radiated by the sending circuit is proportional to the square of the frequency, so that relatively little energy is radiated at low frequencies. Further, if audible frequencies were employed, every sending station would need to use the whole range of audible frequencies, and the possibility of *tuning* to ensure sensitivity of receivers and permit of selecting one station from another would disappear.

Both the broadcasting and the receiving station need tuned circuits. The essential difference is that the sender is tuned to one fixed frequency from which, by federal regulation, it may not depart by more than fifty cycles; whereas the receiver can be tuned at will. Despite differences of flexibility and power, the two tuned circuits are fundamentally similar. Condensers and inductance coils are involved. A simple condenser can be made by mounting two flat metal plates, say a pair of drummer's cymbals, facing each other, with a narrow air space between. If these are

insulated, they will hold a charge of electricity long enough for the purpose of our illustration. The charging gives one plate a certain excess of electrons, the other a deficiency. Now connect the two plates by means of a spiral of coiled copper wire. The excess electrons tend to run through the wire from one plate to the other. But do just enough shift over to neutralize the original excess and deficiency? Does a rope swing which has been pulled out subside merely to its lowest position when released? The swing overcasts, oscillating back and forth before subsiding to rest; and *so do the electrons in our experiment!* The swing overcasts because it has acquired kinetic energy; the electricity overcasts because the surge of electrons through the wire has already stored energy in the space within the coil. When the current changes, some of this stored energy returns to the coil and keeps the electrons flowing. Thus an excess of electrons accumulates on what was originally the positive plate of the condenser; these discharge back, overcast as before — and so on. If no energy were lost in heat or radiated away, the current, once started, would oscillate indefinitely. In actual practice, giant electron tubes as large as a man maintain the oscillations steadily. The characteristics of the condensers and inductance coils determine the natural frequency of the circuit, and the effects of the surges are applied to the grids of the tubes, to render the oscillations self-perpetuating. Thus the continuous *carrier waves* are generated.

In the receiving set, the tuning condensers can be adjusted by turning the knob, so as to bring either more or less of the total areas of the two sets of plates to face one another. By this means, the natural frequency is adjusted to that of a given broadcasting station, and the feeble currents induced by the incoming waves are vastly stronger than they would be if the circuit were not tuned. Here again our rope swing, by analogy, helps us to think along

the right lines. Everybody knows that, in pushing the swing, the pushes should be timed to synchronize with the swing's natural frequency. Feeble impulses, in step with the natural rate of vibration, build up a relatively large amplitude of motion. Just so with the electric impulses.

In the broadcasting studio, the microphone and its accessories vary the *amplitude* of the high-frequency waves in unison with the sound waves. This is called *modulation*. What the receiving set picks up is a continuous *radio-frequency* carrier wave whose amplitude, or intensity, fluctuates at *audio-frequency*. Besides tuning and amplifying, we must therefore get rid of the radio-frequency effect without sacrificing the audio-frequency fluctuations to which our ears can respond. If the radio-frequency currents are fed directly into the sound apparatus, say a loud speaker, the speaker will not vibrate. Like an army mule, which balks when one tries to make it go too fast, the diaphragm of the loud speaker simply stands still if we try to make it vibrate at radio-frequency. It has too much inertia. Hundreds of circuits, embodying several distinct methods of suppressing the radio-frequency effect, have been introduced. There are several ways of connecting electron tubes so that the radio-frequency currents will be *rectified;* the *reverse* half of every radio cycle is wholly or partially nullified. This permits the audio-frequency end of the receiving set to sum up into one pulse all the radio-frequency pulses included in one audio-frequency fluctuation, thus giving audible sound. Many receivers apply the *heterodyne* principle. Here we encounter again the phenomenon of *beats,* which interested us in sound. If two different frequencies are superimposed, they produce a beat wave whose frequency equals the *difference* of the two component frequencies. Our 500 and 512 tuning forks gave twelve beats per second. In the receiving set, one or more

tubes can be devoted to the generation of weak currents of an intermediate frequency; these, superimposed on currents of radio frequency, produce currents whose frequency equals the difference. In the elaborate superheterodyne receivers commonly used, the set itself may be generating a frequency of 950 kilocycles to reduce the frequency from, say, 1000 kilocycles to the difference, 50 kilocycles per second, which is still above the limits of audibility; and another tube may be acting to reduce the 50-kilocycle currents to audible frequencies.

What we have sought here is to understand the reasons for the various operations involved in what was considered, before television came along, the crowning achievement in the field of communication. Hardly a month passes without bringing the news of a new triumph in radio-controlled flying, or direction-finding at sea, or some other extension of this powerful agency which science has placed at man's disposal.

Television

In television, we find the actions of radio, light and photoelectricity cooperating to do for vision what radio has accomplished for hearing. Instead of sound waves striking a microphone, light shining on a photoelectric cell produces the electric currents which modulate the radio waves. Since photoelectric cells are as easy to obtain and to operate as microphones, one might at first thought conclude that television would present no greater difficulties than sound broadcasting; but whereas the microphone accepts the whole sound as a unit, the light-sensitive apparatus used in television must discriminate between the brightnesses of the different points of the object. For example, the faces of two actors might reflect equal amounts of light to the photoelectric cell and thus produce

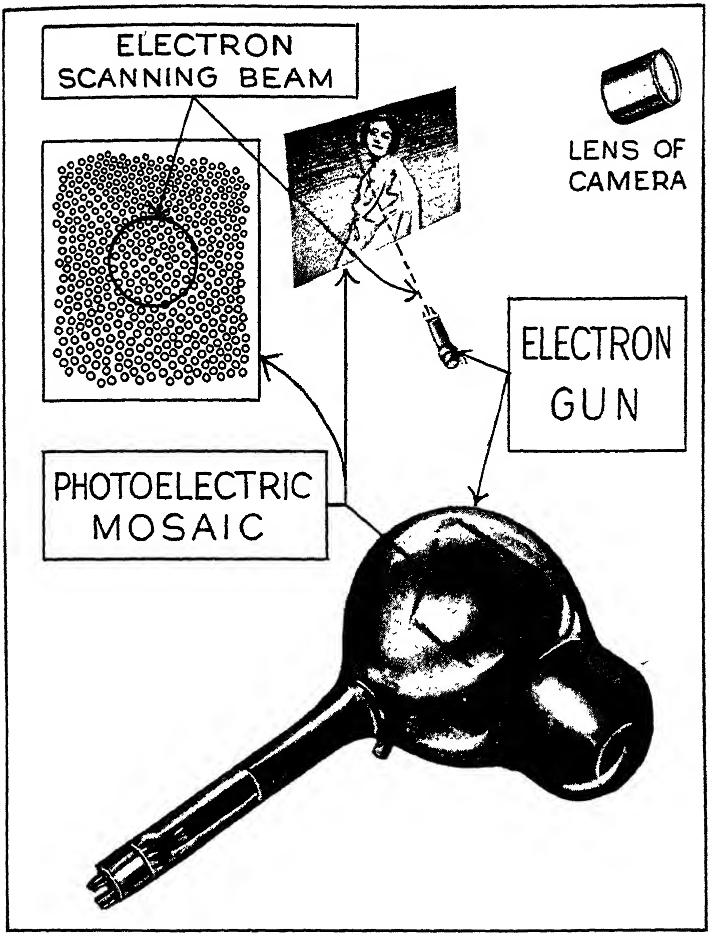


FIGURE 59. Television without mechanical moving parts. A camera forms an image on a mosaic of thousands of miniature photoelectric cells. A scanning beam of high-speed electrons plays back and forth systematically over the mosaic, acting as a switch to turn on one cell after another. Thus a point-by-point transmission is obtained. In the receiver, an electron beam striking a fluorescent screen lights up one point after another so rapidly that the whole screen seems to be illuminated. (Adapted from an article by Dr. V. K. Zworykin in the Journal of the Franklin Institute.)

electric currents of the same magnitude. Merely to transmit the massed effect of the total amount of light reflected by a face or other object would give no distinction between light and shade, hence no recognizable image.

In one system of television, this difficulty is avoided by a means called *mechanical scanning*. Suppose the face of an actor illuminated by artificial light is to be reproduced at a distance. A photoelectric cell looks at the face while a narrow, rapidly moving pencil of light plays over the whole face point by point. A rotating disk bearing a series of holes arranged in spiral fashion accomplishes this systematic scanning of the face by letting light through one hole after another. When the pencil of light falls on one point of the face, say a portion of an eyebrow, little light may be reflected to the photoelectric cell, and the electric current will be small. When the beam strikes a bright region of skin, the current is increased. Electric currents which fluctuate in proportion to the differences of brightness are thus obtained, and these can modulate the radio carrier waves just as well as do the fluctuating currents controlled by the speaker at the microphone. At any one instant, the effect of light from only one point of the face is being transmitted, but if the scanning beam of light travels over the face rapidly enough, the illusion of seeing the whole face all at once can be produced in the receiving station.

The receiving set must perform many of the operations of an ordinary radio set; but instead of controlled sound, controlled light must be produced. In the system using mechanical scanning, one of the quick-acting neon glow lamps is substituted for the loud speaker. The brightness of this lamp fluctuates in unison with the photoelectric currents produced in the studio when the subject is being scanned. The neon lamp illuminates a translucent screen from behind. Between the lamp and the screen is placed

a spirally-holed scanning disk which is made to rotate at exactly the same speed as does the one in the studio. The whole face of the subject is never actually reproduced at one instant on the screen; but the different points of the whole screen are differently illuminated in very rapid succession, so that *persistence* of vision acts to give the illusion of a steady illumination. Every point of the image must be illuminated at least sixteen to twenty times a second. Why the image is formed will be clear if one considers two regions of the screen, say part of an eyebrow and the tip of the nose. Whenever the scanning disk admits light to that portion of the screen where the end of the eyebrow is to be seen, the brightness of the neon lamp has a low value, determined by the brightness of the actual eyebrow in the studio; and whenever the tip-of-the-nose part of the screen is illuminated, the lamp's brightness is greater in proportion to the brightness of the real nose tip.

The method described above has been used with moderate success, but in this country commercialization of television on a large scale has been purposely delayed pending the development of a system whose performance can compare favorably with that of modern radio broadcasting. Apparently, the early stages of radio, in which the reception of anything, no matter how poor the quality, was a popular fad among amateurs, are not to be duplicated in television, at least not in this country. A method involving *electronic scanning,* developed largely in the research laboratories of the Radio Corporation of America, is very nearly ready for commercialization. This method does away with the rotating apparatus which is the bane of mechanical scanning, and seems to be about as well adapted to transmit outdoor scenes, say a football game or a presidential inauguration, as artificially lighted scenes in a studio.

In this system of television, a camera forms an image of the

scene on a screen which consists of a mosaic of thousands of tiny photoelectric cells. This screen takes the place of the film in a camera. Every one of the miniature photoelectric cells is insulated from its neighbors, and every one receives light continuously. The purpose of dividing the photoelectric screen into so many separate parts is to do away with the moving beams of light used in the first system described. In the preliminary experiments with this photoelectric mosaic, every cell was provided with its own connecting wires; but the same effect is now obtained with a single pair of wires. A narrow beam of *cathode rays* (high-speed electrons) plays systematically over the mosaic on which the image is formed. This invisible beam of electrons performs the function of an electric switch, turning on one miniature photoelectric cell after another in rapid succession and thus releasing its electric energy to the single pair of wires. The electric impulses produced by electronic scanning vary in strength according to the brightness of the various points of the image formed on the screen by the camera lens. This is the same result accomplished by mechanical scanning, but does not require that the scene be illuminated by a moving pencil of artificial light. The rotating disk is also eliminated; for the scanning beam of cathode rays is focused and moved about by means of electric and magnetic forces suitably controlled in what is called an *electron gun*.

Recently, the efficiency of electronic scanning has been greatly increased by causing every miniature cell in the mosaic to store up the electric energy produced by the light. Every time the scanning beam of electrons flits across one cell of the mosaic, it releases not merely the photoelectricity produced by the instantaneous effect of the visible light falling on that point, but also the electric energy stored up there by the light since the last time the beam crossed that element. This storing effect is obtained by use

of a well-known device called an electric condenser. This, in its simplest form, consists of two metal plates mounted face to face and insulated from each other.

The receiving apparatus used in the electronic system of television utilizes another scanning beam of cathode rays. At the transmitting end, we remember, the scanning beam performed the function of a high-speed electric switch; here in the receiver its *fluorescent* effect is applied. The moving beam of electrons plays over a screen coated with a fluorescent material which lights up under the impact of the electrons. The brightness of the screen at any given point depends on the intensity of the scanning beam when the beam crosses that point; and since the intensity of the beam at that instant is proportional to the brightness of the corresponding point of the original scene, an image is produced. The scanning beam traverses the entire screen rapidly enough (twenty-four times a second) to produce the illusion of steady illumination. No rotating disk is needed, nor the neon lamp.

A number of practical difficulties, together with the high standards of performance demanded by manufacturers in this country, have thus far delayed the commercialization of television. It seems probable that the next few years will bring this remarkable achievement into daily use. For the present, a less spectacular development in a related field is of greater practical importance. This is the transmission of news photos, documents, fingerprints, identifying signatures and the like by radio. Here the requirements are not as severe as in television; for the element of apparent simultaneity of all parts of the reproduction is not needed. A more leisurely scanning is permissible. But if one cares to pay for the arrangements, it is possible today both to see and to hear almost anything within reason on the face of the earth without stirring from home. We have come quite a distance from the day when

Andrew Jackson thought he was winning a war which had been ended by treaty two weeks earlier.

MATERIAL FOR REVIEW AND SELF-QUIZZING, UNIT 3

TRUE-FALSE REVIEW — Appendix, Part 3.

SUGGESTIONS FOR SUPPLEMENTARY READING AND REFERENCE

The Elements of Chemistry — W. L. Foster (Van Nostrand)
College Physics — A. L. Foley (Blakiston's)
Introduction to Biochemistry — Roger Williams (Van Nostrand)
The Spirit of Chemistry — Alexander Findlay (Longmans)
Science for a New World — Sir J. Arthur Thomson (Harper)
General Chemistry — Smith-Kendall (Appleton-Century)
From Galileo to Cosmic Rays — H. B. Lemon (University of Chicago Press)
A Survey of Physics — Frederick Saunders (Holt)
Speech and Hearing — Harvey Fletcher (Van Nostrand)
Television — RCA Institutes Technical Press, 75 Varick Street, New York City (Vol. 1, July 1936)
Creative Chemistry — Edwin Slosson (Century). (*Note:* An old book (1920) but excellent for background, highly readable, and full of inspiration.)
Principles of Biochemistry — A. P. Mathews (Wm. Wood & Co., Baltimore)

UNIT 4

THE UNCONTROLLED CHANGES, OR GEOLOGICAL EVOLUTION, OF OUR PHYSICAL ENVIRONMENT

CHAPTER 15: *The Weather*

16: *Some Geological Processes at Work*

17: *The History of the Earth*

Chapter 15

THE WEATHER

The changing conditions and actions known as the weather are continually at work modifying our environment. *Climate,* the year-round average of the weather; *seasons,* the gradual changes of the monthly average of the weather; and *weather* itself, the immediate state of the atmosphere at the place and hour in question — we lump these all together under one convenient heading. Night follows day as the earth spins on its axis. Season follows season as the earth plods steadily around the sun at eighteen and a half miles a second. Like a ship circling an island on a leash, a one-funnelled ship rounding the island with a strange forward-sideward-backward-sideward motion that keeps the rakishly tilted funnel pointing in one fixed direction in space, the earth keeps its axis tilted towards approximately the same spot in the heavens as it journeys around the sun. The sun shines on land and water through the thin blanket of air which the earth clutches to its bosom with invisible fingers of gravitation. As a result of all these actions and circumstances we have weather.

Here our point of view shifts to one which may be broadly described as *geological.* For several chapters we have been interested in the amazing transformations which the applications of physical science have wrought in our environment. We have watched science enabling one man to count for a hundred in getting the work of civilization done; we have seen chemists rearranging atoms to make materials which may be unique in the universe; we have studied the means by which ideas are conveyed across the street or around the sphere to accelerate, and indeed make possible,

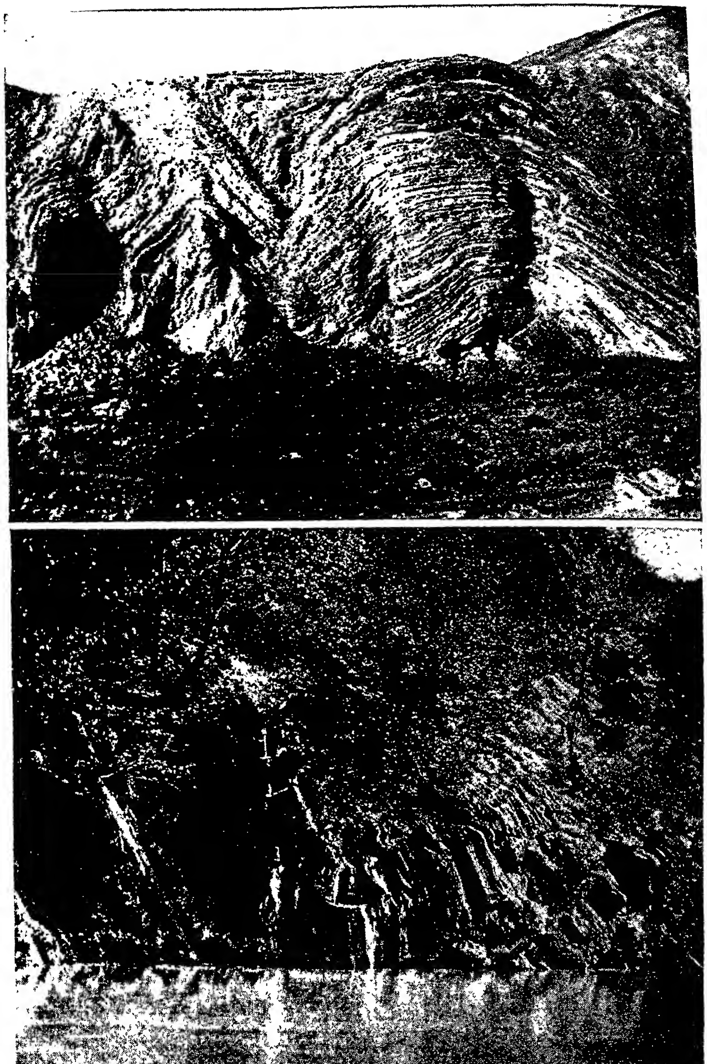


FIGURE 60. Folded Rock. This evidence of geological processes capable of bending thick layers of solid rock into curves suggests that we should not claim too much when speaking of controlling our environment. (All geological photographs in this unit are reproduced from an *Introduction to Physical Geology,* by William J. Miller.)

the evolution of civilization. Now we are turning to those natural agencies of change which are largely uncontrolled. For the benefit of architects, miners, well-drillers, drainage engineers and dam-builders, and in a multitude of projects designed to preserve the soil and to maintain rivers and harbors against the twin processes of erosion and deposition, the geologist applies his knowledge of natural agencies of change and the results which they produce — but these useful applications are made possible by his interest in every natural factor which has helped to fashion the earth's surface layers since our terrestrial sphere began to evolve out of a few bits of matter torn (as best science can tell) from the sun.

In the physical domain there can be no perfectly sharp distinction between natural evolution on the one hand, and forced, or artificial, evolution on the other. The same laws operate in both spheres, and what is not purposely controlled today may be controlled tomorrow. The energy expended in the World War of 1914–18, if intelligently applied to drought-ridden areas, could have changed the surface conditions of large regions permanently. We hear often of the Norris dam, a supposedly gigantic undertaking; but the total direct economic cost of the World War (estimated at $300,000,000,000 for all the nations involved) could have supplied the world with eight thousand Norris dams — an average of thirty for every city in the world as large or larger than Dayton, Ohio. An equivalent expenditure distributed among projects including dams, lakes, connecting canals, reforestation in strategic belts, grading, and, if needed, irrigating pumps operated by the electric power generated at the dams, would reduce droughts and dust storms, retard erosion, and by changing both the heat-radiating characteristics of the surface and the distribution of water and water vapor, slightly modify the weather in certain regions. If this is merely a pleasant dream, then the World War was merely

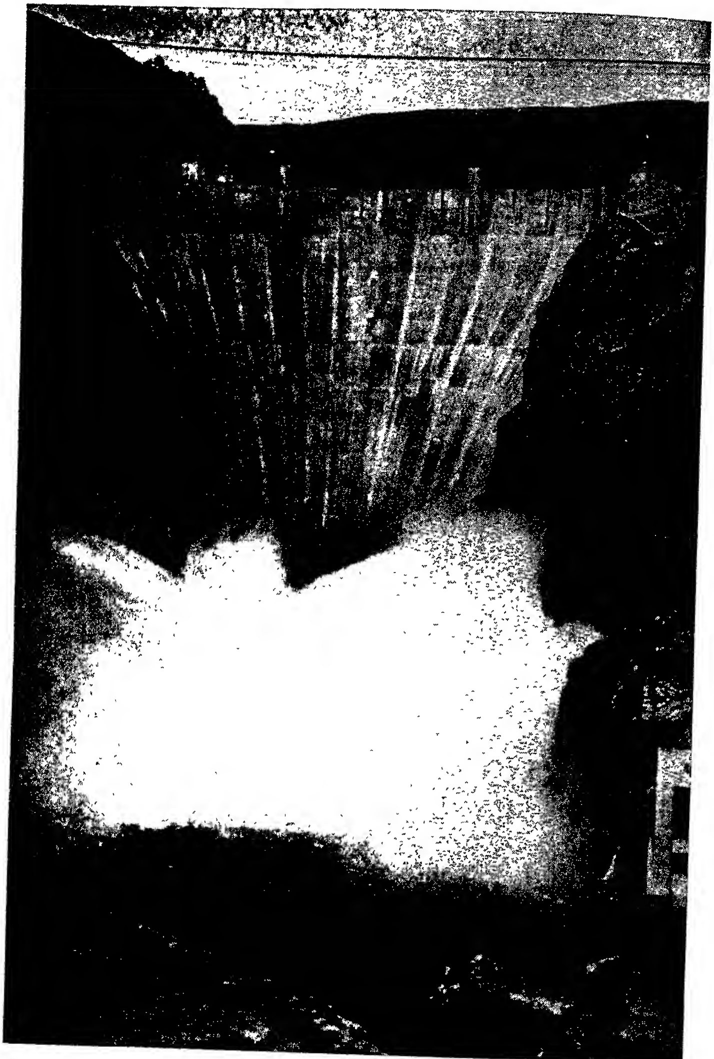


FIGURE 61. Boulder Dam. The waters impounded above this dam will form the world's largest artificial lake, a body several thousand square miles in area. Evaporation, and the thermal sluggishness of the great mass of water, will modify the weather slightly in its vicinity. (Courtesy General Electric Company.)

a bad one. To the student of physical science, whose duties do not include reconciling the conflicting aims of mankind, these are mere questions of matter, energy and the laws of nature. Present knowledge of geology, physics, chemistry and biology, and the superabundance of energy at our disposal — fuel, explosives, water power, tides, winds and direct sunlight — can enable man to do to the surface of this planet at least the equivalent of what Lowell supposed his Martians to have done to theirs.

To one who has known fear in a storm at sea, or cowered in a hole while a hurricane blew away the house above his head, or even stood in a driving rain, we may seem to imply too much. We are not suggesting that hurricanes, trade winds, tides, earthquakes, glaciers or seasons will ever be controlled. For the larger-scale actions which influence surface conditions on the earth, and the more violent, adequate foreknowledge and suitable measures of conservation and protection are probably the best that we may expect. We manufacture a little weather on a small scale, indoors; we build dikes, dams, canals and breakwaters; we cut down forests and plow the soil — but on the whole we do comparatively little to modify geological processes. These uncontrolled actions, then, are the topics with which the present unit is concerned. The subject is large, but much of the material which has gone before will help us to a quick understanding of at least the more important actions. The motions of the earth; gravitation; the sun's radiation; the nature of the atmosphere; evaporation and condensation; freezing and melting; expansion and contraction under temperature changes; chemical transformations; conservation of energy; ionization of gases; the nature of heat — these topics have been dealt with, and all are involved in an understanding of the physical actions which cause our environment to change from day to day and from age to age.

The Seasons

The only satisfactory way to understand the causes of the seasons is to visualize the earth as it makes its annual circuit around the sun. Put a grapefruit on the floor to mark the location of the sun, and several feet away place an orange to stand for the earth. Pierce the orange through its center with a long knitting needle. This is supposed to represent the axis about which the earth spins. To complete the illusion, ink out the equator around the orange halfway between the two poles where the needle protrudes, and label the upper half *northern hemisphere,* and the lower, *southern.*

As a preliminary experiment, set the orange with the protruding needle vertical, perpendicular to the floor, and carry the orange in a circle around the grapefruit without letting the axis incline in any direction from its up-and-down position. By spinning the orange on the needle while carrying it around its orbit, one can quickly see that if the earth's axis were set as the needle is, perpendicular to the plane of the orbit, there would be twelve hours of daylight and twelve hours of night every day in the year everywhere on the earth except at the poles at the ends of the axis. Furthermore, an observer at the equator would find the sun overhead, in the zenith, at high noon every day in the year. At any other latitude the sun, while never reaching the zenith, would stand at the same height above the horizon at high noon every day in the year. It would not move north or south as month followed month. Except for small changes due to the fact that the earth's distance from the sun changes slightly during the course of the year, *there would be no seasons if the earth's axis were perpendicular to the plane of its orbit.*

Now tilt the orange slightly, so that the top of the knitting needle drops about a quarter of the angle down towards the

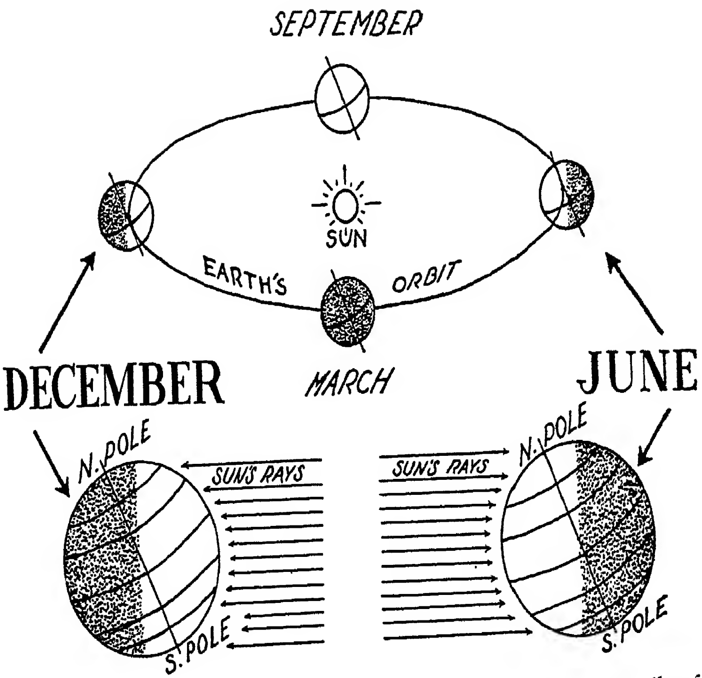


FIGURE 62. Cause of the seasons. The earth maintains the tilt of its axis as it traverses its orbit. Hence the directness with which the sun's rays strike a given latitude, and the number of hours of sunlight in a day, vary from month to month.

horizontal. This corresponds roughly to the true inclination of the earth's axis, which lacks twenty-three and a half degrees of being perpendicular to the plane of the orbit. Carry the orange around the sun without letting the angle of the needle change. No matter where the orange is in its orbit, the needle must remain parallel to its original direction. This corresponds to the behavior of the earth. Except for a slow wobbling which in about twelve thousand years will cause the earth's axis to point to Vega instead of Polaris, the inclination of the earth's axis remains constant. By observing the orange, one can see why we have seasons. At one point in its orbit the north polar region is tilted partly towards the sun, and six months later it is tilted away from the sun. Thus for a few months in the year the northern hemisphere receives the sun's rays *more directly* (more nearly vertically), and for *more hours* out of the twenty-four, than does the southern hemisphere; and six months later the situation is reversed. These are the two causes of the seasons. There is summer in the northern hemisphere when the southern is having winter, and vice versa. Spring and autumn are merely transitional seasons when neither hemisphere is noticeably favored.

By experimenting with the orange, tilting the needle at various angles, one may enjoy speculating on other possibilities. We have already seen how to set the axis to reduce seasonal changes to a minimum. How would one tilt it to make the changes as great as possible? There is no law of nature requiring a twenty-three-and-a-half degree angle of tilt. The earth *might* have been started going around the sun with its axis inclined at any angle! But whatever the tilt, it must remain constant except for the slow wobbling mentioned above.

For accurate work with our model, elevate the orange on a book so that its center is on the same horizontal level as the center of

the grapefruit. Restore the proper tilt to the earth's axis (23.5 degrees from the vertical) and place the earth at that part of its orbit which corresponds to winter in the northern hemisphere. With the aid of a stick, note where a straight line from center of sun to center of earth would strike the earth's surface. The result is, 23.5 degrees *below* the equator. That is the spot which is receiving the sun's rays most directly. Move the orange halfway around its orbit, keeping the direction of the axis unchanged, and repeat the test. In this new position, the straight line joining the centers of earth and sun strikes the earth 23.5 degrees *north* of the equator. Now the northern hemisphere is having summer; the southern, winter. By spinning the orange on its axis in this position, one readily sees that the number of hours of sunlight out of every twenty-four becomes greater and greater as one goes north of the equator, and smaller and smaller as one goes south of the equator. In summer, long periods of daylight when the atmosphere and surface may store up heat, and short nights, hence a restricted opportunity for re-radiating that heat back into space — that is the rule. And the farther one is from the equator, the longer the day and the shorter the night, in summer; the reverse in winter — and at the poles the extreme conditions, six months of uninterrupted daylight, followed by six months of unbroken night.

At the equator the sun is above the horizon for twelve hours out of the twenty-four every day in the year. Halfway up towards the north pole, at the latitude of Minneapolis (45 degrees), the number of hours of sunlight in a twenty-four-hour day ranges from 8.6 hours on December 21 to 15.4 hours on June 21. The corresponding figures for the north pole are zero and 24. These variations in the number of hours of sunlight per day influence the weather, and the daily average of temperature, profoundly; but they are not the sole cause of seasonal changes. At the latitude

of Minneapolis, a square mile of the earth's surface receives more than four times (actually 4.32) as much solar energy on June 21 as on December 21, although the number of hours of sunlight on that June day is, as we saw above, not quite twice as great as on December 21. The additional factor is the increased directness of the sun's rays in the summer. They strike the earth's surface less obliquely, so that a given bundle of radiant energy is concentrated on a smaller area.

The effect of obliquity, or slant, of the sunlight is strikingly brought out by considering the yearly average of the climate at different latitudes. In the course of a whole year, the sun spends the same total number of hours above the horizon for every place on the earth — from the north pole to the south pole — yet the total amount of solar energy received by one square mile of the earth's surface in a year is approximately two and a half times as great at the equator as at the poles. This is the reason the annual average of the temperature decreases steadily as the latitude north or south of the equator increases.

Much could be said about the seasons; but we content ourselves here with two additional facts of great interest. One is the effect of the ellipticity of the earth's orbit, the fact that the earth is about 3.4 percent closer to the sun on January first than at the beginning of July. This means that the whole earth's daily income of energy is greater early in January than it is six months later. Since the amount of energy received by the earth from the sun falls off as the *square* of the distance, the maximum change in a year is not 3.4 percent, but twice that, 6.8 percent. If the earth's axis were not tilted, the whole earth would have a mild summer in January, and a mild winter in July. Actually, this minor effect is superimposed on the seasons caused by the inclination of the earth's axis — with the result that both winter and summer are slightly

moderated in the Northern hemisphere, and rendered more extreme in the southern. The other effect that we had in mind is the lag of the seasons. Absorption of heat by the atmosphere and the earth's surface layers causes the hottest part of the summer to be delayed until a number of weeks after the daily income of energy from the sun has reached its maximum. A similar action causes a delay in the arrival of winter. The amount of the lag depends on the density of the atmosphere. In the thin, dry air of high altitudes, the lag is short.

Winds

The unequal heating of the atmosphere at different parts of the earth's surface is the principal cause of another familiar phenomenon which is uncontrolled: the winds. Air expands when heated. A cubic mile of warm air weighs less, at a given pressure, than a cubic mile of cold air. Therefore warm air floats on cold air. If the two cubic miles of air in question are near the earth's surface, the *difference* between their weights is about ten thousand tons for every degree Fahrenheit of temperature-difference between them. If one cubic mile of air is thirty degrees Fahrenheit warmer than the other, a force of approximately three hundred thousand tons-weight is available to push the warm air upward. Picture a giant beam balance with 300,000 tons more on one pan than on the other. One side goes up. The familiar action of chimneys — *convection* — is going on all the time on a grand scale in the atmosphere at large, without benefit of brick-walled chimneys to guide the draft. Sportsmen experienced in the art of maneuvering motorless gliders find these rising currents of air and hover for hours with no other support. Bare earth lying exposed to the sun is likely to be warmer than the massed leaves of

wooded or grassy lands. The aviator flying near the surface on a still, hot day may notice "bumps" caused by currents of air rising above patches of bare ground, and "holes," or down-draughts, above the cooler well-foliaged areas. Just as cold air rushes into a chimney at the bottom to push up the lighter column of air that has been heated by the fire, so the lower atmosphere everywhere tends to move towards the places where the masses of air pressing down on the landscape are the lightest.

This being true, where on the earth would one expect the atmosphere to be the most turbulent? The emphasis on temperature as a prime factor in the production of winds might easily lead one to arrive at an answer for inadequate reasons. Few spots on the earth are exempt from severe storms. High temperatures alone do not cause winds. *Differences* of temperature must be considered. In discussing the seasons we were interested in the reasons why the average temperature at a given place changes in a systematic fashion as the year runs its course. Now it is the difference of temperature between two regions at a given time that enters the argument. If all the air surrounding the earth remained uniformly at the same temperature winds would be negligible, even if that uniform temperature were as high as the value actually found in the tropics.

But of course there must be a reason why the expression "storms of tropical intensity" has come into the language. Although the angular distance from the south pole to the north pole is 180 degrees, half of the earth's surface, and therefore half of the earth's atmosphere, lies in the sixty-degree belt included between the latitude of New Orleans and that of a place about halfway between Rio de Janeiro and Buenos Aires. The distance around the equator is simply greater than the distance around a smaller circle parallel to it, and there is as much air above this middle third of

the latitude range as above all the remainder of the earth put together. Furthermore, this air receives more heat per square mile of earth-surface than does the air elsewhere, and most of it remains warm month in and month out. At the equator there are twelve hours of daylight every day in the year, and the variation elsewhere in the equatorial belt is not great. Further, the sun is always relatively high in the heavens at noon in the tropics and subtropics. Twice a year it stands in the zenith at the equator at noon, and twice a year there it reaches a maximum angular distance of 23.5 degrees from the zenith — 23.5 degrees south from the zenith on December 21, and 23.5 degrees north on June 21. Hence all through the year the sun's radiation is concentrated on the tropics with great directness, yielding a relatively large amount of heat per square mile of surface.

The lag of the seasons reminds us that a great deal of the radiant energy intercepted by the earth is absorbed by the atmosphere before reaching the surface. The air near the surface of the earth does a disproportionately large share of the absorbing. Half of the whole atmosphere lies in the layer extending only three and a half miles above the earth's surface. Not only is the air denser near the earth's surface, but most of the water vapor — a good absorber — is found there. Further, the rare upper air cools itself by re-radiating heat already absorbed from the sunlight; whereas the layers close to the ground experience an additional warming due to re-radiation of solar energy by the ground. These layers are more nearly opaque to the long heat-waves re-radiated by the surface than they are to the shorter waves of the incoming sunlight. Hence much of the radiant heat is trapped in the lower atmosphere — an effect similar to that produced by the glass roofs of greenhouses and therefore called the *greenhouse effect*. What we have to consider, then, is the role that convection plays in an at-

mosphere whose lower layer — and of that lower layer the tropical part — is most strongly affected by the sun.

Denser air flows in towards the equatorial zone from both sides, pushing the lighter air up. The surface winds which result — the *trade winds* — blow towards the equator, but not directly. For a reason to be considered in a moment, they are deflected westward. The warm air displaced upward at the equator cannot continue to rise indefinitely; it spreads out towards the poles, flowing north and south from the equatorial belt. These higher currents are called the *anti-trade winds.* Where air is rising or descending, *calms* may result. The surface winds blowing into the equatorial belt from opposite directions tend to neutralize each other and produce the calms sometimes called the *doldrums.* The air that is pushed upward from the equatorial belt descends again after being cooled. Much of it strikes the earth's surface near the outer boundaries of the tropic zone (*the horse latitudes*), producing the *calms of Cancer* in the northern hemisphere and the *calms of Capricorn* in the southern. Readers who delve into the literature of the days when sailing ships carried the world's overseas commerce will encounter these terms again and again.

The direction of winds, and to some extent their energy as well, is affected by the *rotation of the earth.* Here we must remind ourselves of the wide range of surface speeds of the spinning earth. A rock on the earth's surface at the equator travels at the rate of 1041 miles per hour in order to get around the equatorial circumference — 24,902 miles — in 23 hours 56 minutes. At New Orleans the surface speed is 893 miles per hour; at New York 800; at Nome, Alaska 456; and precisely at the north or south pole of the earth, zero miles per hour. If the earth rotated under a stationary atmosphere, there would be tremendous winds all the time, the most violent at the equator — and the earth would gradually be slowed

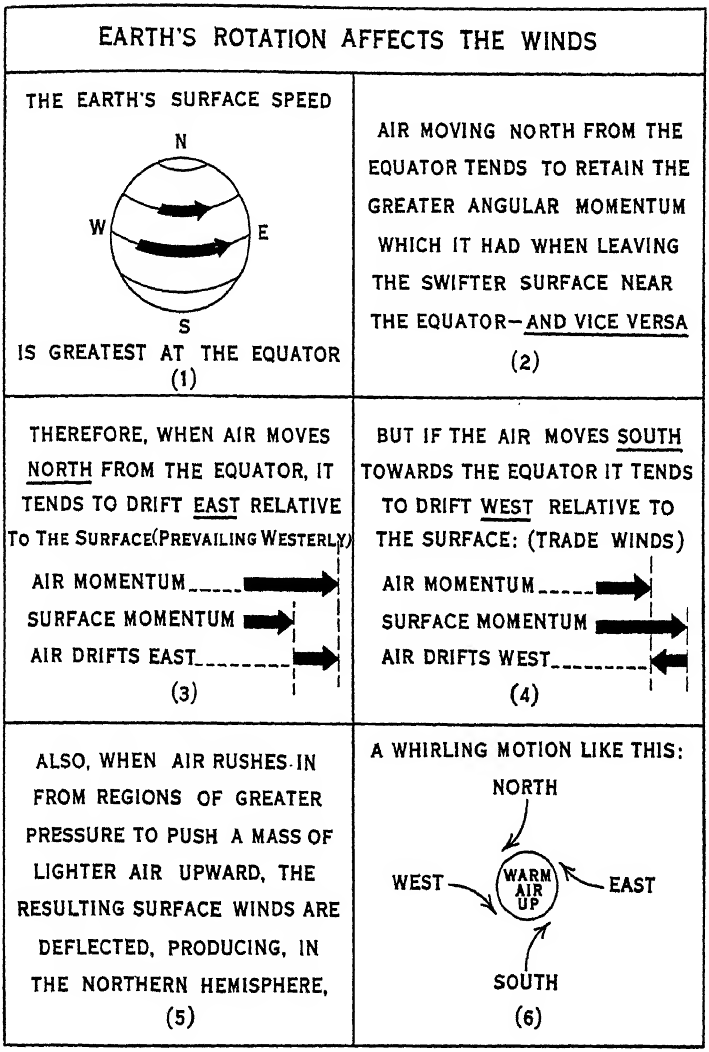

EARTH'S ROTATION AFFECTS THE WINDS
THE EARTH'S SURFACE SPEED
N
W
E
S
IS GREATEST AT THE EQUATOR
(1)
AIR MOVING NORTH FROM THE EQUATOR TENDS TO RETAIN THE GREATER ANGULAR MOMENTUM WHICH IT HAD WHEN LEAVING THE SWIFTER SURFACE NEAR THE EQUATOR—AND VICE VERSA
(2)
THEREFORE, WHEN AIR MOVES NORTH FROM THE EQUATOR, IT TENDS TO DRIFT EAST RELATIVE TO THE SURFACE (PREVAILING WESTERLY)
AIR MOMENTUM
SURFACE MOMENTUM
AIR DRIFTS EAST
(3)
BUT IF THE AIR MOVES SOUTH TOWARDS THE EQUATOR IT TENDS TO DRIFT WEST RELATIVE TO THE SURFACE: (TRADE WINDS)
AIR MOMENTUM
SURFACE MOMENTUM
AIR DRIFTS WEST
(4)
ALSO, WHEN AIR RUSHES IN FROM REGIONS OF GREATER PRESSURE TO PUSH A MASS OF LIGHTER AIR UPWARD, THE RESULTING SURFACE WINDS ARE DEFLECTED, PRODUCING, IN THE NORTHERN HEMISPHERE,
(5)
A WHIRLING MOTION LIKE THIS:
NORTH
WEST
WARM AIR UP
EAST
SOUTH
(6)

Figure 63.

down by air friction. But of course the atmosphere as a whole has picked up—and retains—the rotational motion of the earth. However, it is not fastened to the earth except by gravitation, and when a mass of air moves north or south, from one latitude to another, *it tends to retain the rotational momentum that it possessed at the latitude from which it came.* This effect is nearly analogous to the behavior of an apple tossed vertically upward in a moving train: the apple retains its forward speed while going up and down, hence does not lag behind. And it is *entirely* analogous to the effects brought to light by our spinning stool experiment, back in Chapter 3. If the air has a certain angular momentum eastward, it is not going to give up some of it, or gain more, instantly, merely in order to accommodate a region of the earth that has a different eastward speed.

Consider, then, what would happen if a great mass of air moved quickly from New Orleans to the equator. At New Orleans, merely in order to remain at New Orleans, it was moving eastward at the rate of 893 miles per hour. Arriving at the equator, it finds the surface moving eastward much faster—1041 miles per hour. The air from New Orleans is now going too slowly to keep up with the surface. It lags behind. From the point of view of the surface dweller at the equator, it is moving *westward.* This same effect must be taken into account in long-range gunnery. The seventy- to eighty-mile shells launched at Paris during the World War would have missed their marks if the deflection en route due to the different surface velocity of the point of destination had not been included in the calculations. To predict the effect quantitatively, it is not enough merely to subtract the surface speeds at the two latitudes in question. The changing radii of the parallels of latitude must also be considered. But the direction of the effect is easy to predict. Air moving towards the equator is de-

flected westward. Hence the *trade winds* blow towards the southwest in the tropical and subtropical regions north of the equator, and towards the northwest below it.

Meanwhile, what is happening to the air that is displaced away from the equator by the incoming winds? The eastward velocity of this air when leaving the equatorial belt is greater than the eastward speed of the surface at the latitudes to which it is going. Hence, on arriving, it finds itself going more than fast enough to keep up with the surface of the spinning earth; it moves east relative to the surface. Thus we see that air moving north or south from the equatorial belt is deflected eastward. In the temperate zones, where most of this air goes, the prevailing wind is towards the east, or, as usually described, from the west. This west wind — the *prevailing westerly* of the temperate zones — is especially noticeable above the oceans and at the higher altitudes, where local disturbances due to surface irregularities are not sufficiently frequent or intense to mask the general trend of the air. Wind-records made on Pike's Peak show about seventy percent coming from the west.

There we have, in broad outline, the results produced by nature's giant ventilating system. The mainsprings of the system are the sun's excessive heating of the equatorial air, and the rotation of a spherical earth — and as a result, we find air rising from the equatorial belt, descending again in higher latitudes, circulating in general eastward in the temperate zones; while from both hemispheres air moves continually towards the equator and there circulates westward against the spinning earth.

One important result of this planetary circulation is the production of *ocean currents*. The frictional grip of the air (the same grip that the pouring of oil on troubled waters is intended to loosen) is sufficiently strong to set water to moving in the general

direction of the prevailing winds. In the equatorial belt the trade winds urge water towards the equator and westward along it, and in the temperate zones the water tends to drift eastward under the push of the prevailing westerly. Continents standing across the lines of flow modify the currents. The Gulf Stream, for example, results from the deflecting effect of the northern coast of South America. The westward equatorial stream is deflected northward towards the Gulf of Mexico. After leaving the Florida Coast, the Gulf Stream continues northeastward to about the latitude of Nova Scotia. There it divides. Part returns to the equator, and part continues on towards the Arctic Ocean, passing between Greenland and the British Isles. Great Britain lies as far north as the lower three-quarters of Canada's Hudson Bay, yet, partly as a result of the Gulf Stream, enjoys an equable climate — an eloquent testimonial to the importance of wind-driven ocean currents. Of course the presence of the surrounding water alone would moderate the climate considerably.

In addition to the prevailing winds, local disturbances due to many causes are continually occurring. A few of these may be mentioned. The equatorial belt is not the only place where currents of warm air rise. Whenever a vertical column of the atmosphere becomes lighter than columns of equal cross-section adjacent to it, the greater pressure around it will push it upwards. The incoming air constitutes surface winds. Air rushing in from the north is deflected westward (in the northern hemisphere) as a result of the earth's rotation; air coming in from the south is deflected eastward. Hence a whirling motion is set up, which may produce a cyclone of great intensity. The center of the disturbance is what the meteorologists call a "low," meaning an area of low pressure. This low, with the air whirling around it in a sense opposite to that of the hands of a clock lying face-up on the ground, will in general advance across the country at a speed of several

hundred miles a day. In the United States, the disturbance usually advances eastward (remember the prevailing westerly), and may also be deflected towards the north. The local velocity of the winds whirling around the low-pressure center bears no direct relation to the rate at which the disturbance as a whole advances across the country. The local velocity may range from a few miles per hour to a hundred or more; whereas the speed of advance is such that, as a rough rule, one may usually expect in the northeastern parts of the United States the kind of weather that existed a day earlier about six hundred miles to the west or southwest. The numerous departures from this rule are the bane of the meteorologist, but weather predictions are, in the main, amazingly dependable.

A circular whirling motion of the air may also be started by the combined effects of local heating and the arrangement of obstacles which deflect the inrushing air. Miniature whirlwinds thus caused are often noticed carrying a few leaves or dust upward from a small area.

The presence of water influences the winds. Consider the seashore. During the day the land (hence the air immediately above it) heats up more rapidly than does the water. A convection breeze towards the land—the *sea breeze*—results. During the night the opposite effect occurs. Land is a better radiator than water, and also possesses a smaller thermal capacity. Hence the land cools more rapidly, and the heavier cool air moves outward, forming a *land breeze* that blows from the shore.

Rain

The same convection currents which have figured so prominently in our brief study of winds are responsible also for the production of conditions favoring rainfall. Water is continually

evaporating from oceans, lakes, rivers, vegetation, and from the moist earth itself. We saw in Chapter 8 that water must absorb a large quantity of heat in order to evaporate. The latent heat of vaporization of water depends on the temperature at which the evaporation occurs. The average value is about five and a half *times* as great as the amount of heat required to warm the same quantity of water from the freezing temperature to the boiling point, under standard conditions of pressure. It is easy to see that here is another important service which the sun's radiation renders to man: it supplies the enormous quantities of heat that are needed merely to evaporate water without making it any warmer.

Now suppose that a column of warm, moisture-laden air is being forced upward by adjacent masses of cooler air. The rising air is not saturated when it starts its ascension—but a change occurs. The pressure of the air grows less and less as the air rises to higher altitudes. Under reduced pressure it expands—and expansion, as we discovered in Chapter 8, is one of the two cooling processes which are applied in artificial refrigeration. The rising air becomes colder because of its expansion. Another action—one of less importance—promotes the same end: the air has improved opportunities for radiating its heat away as it enters the region where the atmosphere is less dense.

Cool air cannot hold as much water vapor as warm air can. An amount of water vapor that just barely falls short of saturating one cubic foot of air at 80 degrees Fahrenheit is enough to saturate nearly *four* cubic feet at 40 degrees. The vapor in the ascending column of air, though not sufficient to saturate it when it was warm, may be more than enough to produce saturation at its new lower temperature. The excess tends to condense in the form of tiny particles of liquid water, and actually will condense if

the air contains particles of dust or smoke to serve as nuclei, one for every drop of water that is formed. Dust and smoke are condemned as nuisances in the lower air that we breathe — but drifting into the upper air they make an important contribution to man's welfare. Without nuclei around which to condense, the vapor, even if supersaturated as a result of the cooling, will not form drops of water. In Chapter 10 we read of C. T. R. Wilson's cloud-chamber method of rendering the paths of single alpha particles visible, and photographing them. The speeding alpha particles break up molecules into electrified ions; these serve as nuclei on which water condenses when the air is cooled by a sudden forced expansion. Professor Wilson merely produced on a small scale the actions which cause clouds to form in the atmosphere. The dust storms which sometimes occur in drought-stricken areas satisfy *one* of the conditions necessary for breaking the drought. They fill the air with nuclei on which raindrops can form if any vapor is waiting, ready to condense.

Even after the vapor has condensed, rain may not fall. The clouds that we see are not composed of vapor; they are liquid water. (An exception should be noted. The highest clouds consist of solid particles of ice, not liquid. *Snowflakes* are the result of the condensation of water vapor at a temperature below freezing. These ice crystals, if very tiny, may hover without falling appreciably, just as do the small particles of liquid water whose behavior is being considered here.) Water vapor itself is an invisible gas. The minute droplets of water comprising the clouds are so small that they fall very slowly. The force urging a drop to fall is its weight; the falling is opposed by air friction. The weight of the drop is proportional to the *cube* of its diameter, but the retarding friction depends on the area of the surface, which is proportional to the *square* of the diameter. A drop having half the

diameter of another weighs only *one-eighth* as much but possesses *one-fourth* as large a surface area. Hence we find the weight decreasing faster than the air friction when we consider smaller and smaller drops, and air friction becomes relatively more important. The clouds which sometimes hover for days over a given spot are composed of liquid water in particles so small that the air friction needs very little assistance to keep the cloud from falling. The necessary assistance is provided by the upward pressure of rising columns of air.

The argument can be completed very quickly. A drop of water one-fiftieth of a millimeter in diameter would require nearly two days to fall a mile in stagnant air. Drops of twice that diameter (hence eight times the weight) fall barely fast enough to be called rain instead of fog. Drops a whole millimeter in diameter have a maximum terminal velocity of about 13.5 miles per hour. (By the time falling bodies have attained what is called their terminal velocity, air friction has become equal to their weight, hence they cease to gain speed.) Larger drops fall faster still, up to a maximum of approximately 18 miles per hour. A higher speed causes a raindrop to break up into smaller drops, which fall more slowly. The conclusion is obvious. If rain is to fall, the rising air must contain so great an abundance of water vapor that when condensation occurs as a result of the cooling, water will keep on condensing after the first minute droplets are formed. These droplets then serve as nuclei for the additional condensation — or small droplets may be formed so close together that they coalesce. The action must continue until drops large enough to fall rapidly have been formed, otherwise clouds or fog will be formed. (A fog is merely a cloud formed near the earth's surface.)

A number of interesting questions can be answered if we keep these general facts about rain in mind. For example, why is it that

heavy rainfall so often accompanies violent windstorms? The condition for rain is a rising column of moist air. The air does not ascend of its own accord; it is pushed up by surface winds flowing in at the bottom. When the moisture in the column turns to rain, the heat which was absorbed when water evaporated to form the vapor is returned to the air as heat. We have already learned how large the latent heat of vaporization is. The heat of condensation is precisely as great. The heat that disappears when water evaporates reappears as heat when the vapor condenses. The formation of coal affords a long-range storage of the sun's energy; the formation of water vapor affords a short-range storage. A good all-night rain can easily build up one inch of rainfall. Suppose the precipitation of one inch occurs in twelve hours. *In that case, heat energy is liberated by the condensing water vapor at the rate of nearly five million horse-power per square mile.* To express it another way, the total amount of heat liberated by the formation of that inch of rainfall is nearly as great as the area rained on would normally receive from the sun in four days. This heat tends to accelerate the rising of the column of air that is yielding the rain. The column is rising because it is lighter than the air around it; the heat makes it lighter still, increasing the disparity. The surface winds that are rushing in to force it up increase in intensity, and soon a violent storm may be in progress.

Knowledge of the causes which produce these ascending columns of air is by no means complete; but there is no doubt that the heat liberated during the early stages of a copious rainfall aids the upward motion of the column whose ascent is causing the rain. One is reminded of the automobile turning turtle on a curve: the starting to tip increases the tendency to tip. But in the case of the rising air column, one should remember that it cannot produce rain unless it is charged with water vapor. Furthermore,

the heat freed by the condensation opposes, to a certain extent, the cooling due to expansion of the rising column. There are many factors involved in dealing with storms, some of them not yet understood. We content ourselves here with sketching the principal tendencies.

Another question: Why is the equatorial belt a region of heavy rains? We have already observed that the air currents there are mainly ascending. This is the condition for rain provided the air is laden with moisture. And it is: The high temperature promotes evaporation.

Turn to our own Northwest. The coastal sections of Oregon and Washington, lying west of the Rocky Mountains, are plentifully supplied with rain. The states lying east of these, on the other side of the mountains, receive much less rain. Why? One reason is that the prevailing westerly blows across Oregon and Washington from the Pacific Ocean. The mountains deflect it upward; expansion, cooling, and rain result. Here the mountains serve as a substitute for convection in producing rising columns of air. The same westerly, continuing across the mountains, descends to lower altitudes, where the pressure is greater, and is there compressed. Expansion is a cooling process; compression is a warming process. Not only has the wind given up a great deal of its water vapor before crossing the mountains; but its tendency to yield rain is reduced by the warming caused by the descent to regions of greater pressure. In our own Northwest the dry wind that results is called the Chinook; a similar wind in the Alps is called the foehn. The region between the Rocky Mountains and the Mississippi River is, on the whole, meagerly supplied with rain. As a general rule, mountains are well watered on their windward side but relatively dry on their lee. The contour of the surface and the direction of the prevailing winds are two of the

influential conditions which help to determine the average annual rainfall in a given area.

One other example of conditions which may give columns of air a motion of ascent, and we must pass on. The trade winds blow towards the southwest across the peninsula of Florida, bringing moisture from the Atlantic Ocean. On the eastern shore, they reinforce the sea breeze. Above the land, which warms up in the sunshine more rapidly than the ocean, ascending columns of air are common. Thus the trade wind coming in cooperates, assisting the upward movement, and a relatively heavy annual rainfall results. But as a rule, no one simple explanation accounts for the regional distribution of rising currents of moist air. The proximity of large bodies of water is one important factor. The Gulf States, for example, lie in the horse latitudes, where most of the arid regions of the earth are to be found—the result of the descent of air which was displaced upward in the equatorial belt. Yet the Gulf States enjoy a large annual rainfall. There are other processes besides ascension which can cause the cooling that is necessary to condense water vapor—cooling by radiation, by blowing over cold surfaces, by mingling with a current of cold air—but the cooling of ascending air by expansion is by far the most important. The high average of about sixty inches of rainfall annually in a narrow strip extending from New Orleans to North Florida testifies to the effectiveness of the Gulf in promoting ascension.

Quick Answers to Familiar Questions

The subject of the weather is a large one. Phenomena close to us give easy clues to actions which sometimes excite wonder when occurring on a grand scale. On a cold wintry day we see a white

cloud forming behind the automobile's exhaust or before the breather's face, and in it we recognize in miniature a counterpart of the fleecy cloud floating overhead. Dewdrops glistening on a cool leaf; rivulets trickling down the outer surface of a pitcher of icewater; raindrops building themselves around nuclei of dust or smoke or electrified ions—the basic principles of condensation apply equally to all three. A cloud in the sky, dew on the windowpane, or a fog shrouding a swamp or obscuring traffic on a London thoroughfare, are all to be understood by looking for the source of the vapor and a cooling action to make it condense.

Questions arise, certainly. When dew forms on the windowpane of a heated house in the wintertime, why does it form on the inner surface? We have grown used to the idea that the air is usually expanding when clouds are being formed in the sky, whereas the warm air of the room must contract when encountering the cold windowpane. But the expansion of the rising column that formed the cloud was merely one method of cooling the air, and here is another: contact with a cold surface. Does the air in a heated house in winter seem much dryer than that outdoors? Very likely it contains as many grams of water vapor per cubic yard as does the air outdoors—but warm air can hold more water vapor than cold air can. With merely an equal quantity, warm air is *relatively* dryer. Good air-conditioning apparatus controls humidity as well as temperature; but at least we can all add *some* water vapor to the air whenever we heat our houses.

We watch the motorless glider hovering aloft, and then look to our chimneys to observe on a small scale the same action of convection that may be sustaining the glider. Seeing the leaves rise where the wind that carries them is deflected upward by a brick wall, we note another means (if a mountainside be substituted for the wall) of sustaining the glider—and in the same

upward deflection of the current we recognize the kind of action that helps to produce rain on the western slopes of the Rocky Mountains. Or, still thinking about ascending currents, suppose some raindrops are carried upward after they have formed — high enough to freeze? Hail forms. If the hail gets wet, then is carried aloft again and the added water frozen, larger hailstones result. But if the air where the water vapor condenses is below the freezing point of water, the vapor condenses directly into solid, forming beautiful crystalline patterns which one can see by putting a snowflake under the microscope. The highest clouds, those called cirrus and cirro-stratus, are composed of miniature ice crystals too small to fall as snowflakes. Such crystals in the atmosphere are responsible for the occasional appearance of a halo around the moon or the sun. The whole subject is intricate; but even a few general principles help us to recognize the broad outlines of the plot that underlies nature's never-ending atmospheric theatricals.

Chapter 16

SOME GEOLOGICAL PROCESSES AT WORK

We now turn from weather to *weathering* — and to a number of other actions which are continually at work modifying our environment. The surface of the earth is a place of turmoil. Wind, rain, floods, tides, ocean waves and landslides; glaciers, avalanches, geysers, volcanoes and earthquakes; water flowing in river beds or percolating through the porous rocks; dissolving of rock and precipitation of the dissolved minerals elsewhere; heating and expansion; cooling and contraction; freezing and melting; the burrowing of worms, ants and roots; a daily income of some twenty million meteors; chemical decomposition and combination; bacterial action in the soil; the dying of millions of marine animals daily — the earth of tomorrow is being fashioned today. On every hand we see in action a multitude of processes which have been at work for ages making the earth that we now know, some of them ever since the matter now composing the earth was torn from the mother-sun several billions of years ago. To become proficient in geology, as in any field of human endeavor worth mastering, requires close attention to details and some years of experience; but scattered all over the earth one finds amateur geologists by the hundreds of thousands, interesting people who by a relatively painless process of observation and reflection have added one new pleasure to the joys of inhabiting this terrestrial ball. Who can sit on the beach letting the grains of fine clean sand slip through his fingers without wondering how the sand was formed and how it came to be there, or stand confronting one of those bare stratified

mountain walls whose layer-on-layer rock formation and embedded marine fossils show that they were built beneath the ocean depths, without speculating on the forces which made the earth heave upward and thus reared the mountains towards the sky?

The Interior of the Earth

Before plunging into a discussion of the various processes which are at work changing our environment, let us take a quick look at the earth as a whole. Our introduction to astronomy in Chapters 2, 3, and 4 gave us fairly clear ideas of the size, shape, mass, atmosphere and motions of the earth, and of its rank among the bodies included within the solar system. What we have to deal with is an *atmosphere,* with which we are already familiar; a *hydrosphere* covering approximately 143 million square miles (about three-fourths) of the earth's surface with water; and a *lithosphere,* the main solid body of the earth.

The portion of the earth which has been investigated by direct means is of course very small in comparison with the whole. The highest mountains tower about six miles above sea level; the deepest ocean beds lie about six miles below it. A total range of twelve miles does not seem very large when compared with the earth's radius of nearly four thousand miles. A few holes about two miles deep have been dug in the earth, and aviators have ascended some fourteen miles into the stratosphere. The results obtained by studying the thin outer layer which is accessible must be supplemented by indirect evidence if we are to form a reasonably sound picture of the interior of the earth. Volcanoes and hot springs, together with man's natural fear of fire as a means of punishment, no doubt figured among the factors which led early peoples to picture the interior of the earth as a place of

fire. Indeed, until very recently many geologists believed on scientific grounds that the central part of the earth was molten.

Fortunately, a number of indirect means of investigation are available to geologists in seeking the answers in this field. One of these is a comparison of densities. The size and mass of the earth have been known accurately for longer than a century and a half, and from these it is a very simple matter to calculate what the average density of the earth is, in pounds per cubic foot. This value may then be compared with the average density of the materials found in the accessible outer layer. The comparison leads to a striking—and inescapable—conclusion. The central core of the earth is several times as dense as the outer layer! The average density of the earth is 5.51 times that of water; but the outer crust averages only about half that, or 2.7. Obviously, the inner regions must be considerably denser than the over-all average of 5.5 in order to compensate for the relative lightness of the crust materials.

This result seems to shatter the ancient central-fire hypothesis; but it leaves two possibilities open. The denser inner core might be so extraordinarily dense as to compensate for lightness elsewhere without being very large, or it might be large and of only moderately high density. A possible clue comes from the heavens. The meteorites which crash into the earth's surface are found to consist largely of iron, nickel and rock. Meteors are astronomical bodies, and so is the earth; and many lines of evidence point to the conclusion that, chemically speaking, the heavenly bodies are sisters under the skin. Examination of hundreds of meteorites reveals amounts of iron and nickel which are vastly larger, relative to the whole mass, than the quantities found in the earth's crust. Where then, one asks, is the remainder of the earth's allotment of iron and nickel? Iron is 7.8 times as dense as water; nickel, 8.9. An

inner core of iron, or of iron and nickel, would provide the extra denseness that we know exists deep in the earth, and would remove the apparent discrepancy between the composition of the earth and of meteorites.

Other clues come thick and fast. Experiments with long pipelines buried horizontally in the earth and partly filled with water show that the moon and the sun produce tides not only in water, but in the solid earth as well. The discovery that the earth-tides do not lag behind the water-tides in the buried pipes, as they would if the earth were viscous, proves that the earth is rigid — and the amount of the yielding is a measure of the rigidity. The earth as a whole turns out to be somewhat more rigid, or stiffer, than steel. Again a core of solid metal is suggested — and away goes the idea (held by many until very recently) that the earth's crust floats on a molten interior. True, the earth-temperature rises as one descends into a very deep hole, but we saw in Chapter 4, when considering Lord Kelvin's understandable error in calculating the age of the earth, that the heat produced by radioactive elements in the earth's crust readily explains the flow of heat. We live on a *solid* earth that is more rigid than steel, and there is no need to believe that the core is a region of extraordinarily high temperature.

Additional evidence supports this view. The earth's axis, like that of a spinning top, wobbles. The wobble is slow, but in about twelve thousand years will move the pole of the heavens some fifty-one degrees, and Vega will become our north star. This wobbling is caused by the gravitational pull of the moon and the sun; but the gravitational inequalities are due to two conditions: the equatorial bulge, and a lack of uniformity in the way matter is distributed throughout the solid earth. Calculations based on this effect suggest that the density of matter in the earth increases from

the value of 2.7 at the surface, to about eight halfway in, and approximately eleven at the center. Under the tremendous pressure at the center of the earth (estimated at three million tons per square foot) a solid metal may be expected to have a higher density than that found in the laboratory.

Finally, as our fifth kind of evidence, and one of the most dependable, there is a mass of seismographic records showing the rate at which the three different wave disturbances caused by earthquakes are propagated. An earthquake produces two different kinds of waves (called longitudinal and transverse) which travel through the body of the earth, the longitudinal waves traveling the faster—and the seismograph also records a third set of waves which arise when the first two strike the earth's surface layer. The lapses of time between the arrivals of the three different waves at a given seismograph, or of a given type of wave at three different stations, reveal to the initiated where the earthquake occurred; but the geologist intent on discovering the earth's secrets finds another use for the records. The existence of a transverse wave that can apparently be transmitted through the entire earth establishes the earth's internal rigidity, for liquids cannot propagate waves of this kind; and the speeds of the longitudinal and transverse waves suggest probable values for the sizes of the different shells of matter which make up the earth.

Cutting a long story short, and summing up, we may take it as proved that this spinning ball on which we live is solid, and more rigid than steel. We know also that the average density is about seventy percent of that of steel, and that the material forming the inner core is considerably denser than the iron that is measured in our laboratories up here on the earth's surface. Probably, but not necessarily, the inner core is very warm, though not hot enough to keep any considerable portion of the material in a molten condi-

tion. Further than that, we cannot speak with confidence. Informed opinion leans toward the idea that the dense inner core is largely iron and extends approximately 2000 miles outward from the center. Around that there seems to be a fairly well-defined shell more than a thousand miles thick, possibly composed of the sulphur compounds of iron and nickel. This leaves a thickness somewhat less than a thousand miles for the outermost layer. The seismographic records of earthquakes suggest that the outermost layer is almost homogeneous, containing no abrupt transitions or discontinuities in its structure; but experiments with pendulums that are sensitive enough to indicate the heavier parts of the earth's crust give some evidence pointing to a fairly abrupt transition from one layer to another somewhere about fifteen to sixty miles below the earth's surface.

According to one view, the crust periodically readjusts itself so as to keep the pressure approximately the same all over the bottom of this thin outer layer. As mountains wear down they press more lightly on the rock beneath them; and the material they lose, finding its way to the sea, increases the pressure there. When the difference of pressure becomes great enough, the crust yields, the heavier portions slipping sidewise and forcing lighter regions up to form mountains anew. The behavior here reminds one of the continual displacement of light warm air by cold air in the earth's atmosphere. If this isostatic action occurs (the theory is called isostasy) one would expect mountains to be lighter, on the whole, than equal volumes of low-lying rock, and such gravitational measurements as have been made show that they are. But we shall have to return to mountain-building after we have considered some of the geological processes that are working to change the earth. Rival views of the behavior of this thin outer layer are in the field, and indeed there is still a question whether an

equal-pressure zone actually exists a mere few tens of miles beneath the earth's surface.

The Weathering of the Earth's Crust

"Mountains to the sea" might be the title of an interesting book. There is undue simplification in the wording—but in the main the connotation is correct. Forces are continually at work tending to level the earth's surface. The highlands are worn down, the ocean bed built up. If no countervailing actions, no upbuilding, occurred, the earth's surface would one day be level. What actions produce this continual trend towards leveling?

A department store may have a shipping clerk and a crew of errand boys. The shipping clerk puts up the purchases in convenient form for transportation, and the delivery crew takes them to their destinations. In the great storehouse of the earth's crust, a somewhat analogous situation obtains. But alas for the dignity of the shipping clerk! The same agencies that prepare the earth's crust for shipment must often turn errand boy and deliver it as well. Fundamentally, though, gravitation working in many guises is the chief agent of transportation, and weathering of all sorts, including chemical weathering, is the principal action that prepares the rocks for their downward journey.

Consider a great block of granite (synonym for permanence!) resting exposed to the weather on a sunlit mountain slope. The surface layer of the granite may become very warm under the hot mid-day sun—but not so the interior. Granite is a poor conductor. A cube of solid copper one foot each way conducts 450 calories of heat every second when one surface is warmer than the opposite by thirty degrees Fahrenheit; but if the block were granite instead of copper, the flow of heat through it would be only a little over two

calories per second. Granite is approximately two hundred times as poor a conductor of heat as the metal that we chose for comparison. So in the daytime the interior of our granite block remains relatively cool while the outer layer warms and expands; and at night the exterior, cooling more than the main body, contracts away from it. Granite expands approximately the same amount as does common glass — and we all know what may happen when one surface of a thick glass tumbler is quickly heated, as by pouring boiling water into it. The change of size of *part* of the glass may break it. Granite, too, strong as it is, can break. If the outer layer is so heated that it tends to expand a sixteenth of an inch, to prevent the expansion by main force would require the same force that would be needed to *compress* the granite a sixteenth of an inch. Under the enormous forces brought into play by the daily heating and the nightly cooling, the rock at length yields. The top layer shears away and falls off, exposing a fresh surface to a similar fate. Who has not seen these thin broad fragments lying around the base of a massive rock? The turbulence of the atmosphere springs to mind at once when the weathering of rocks is mentioned, but here in differential expansion we find an important disintegrating factor that would be effective even if the earth, like the moon, had no atmosphere. Recollections of walking barefooted on the hot dry sand of a bathing beach in mid-summer remind us how great the temperature changes may be.

Disintegration of massive rock by this means is called *spalling*. Any conditions which tend to promote great and frequent changes of temperature promote the action. Under severe conditions the surface temperatures of rocks (not necessarily of the air) may drop from a mid-day high of 130–160 degrees Fahrenheit to a nocturnal low possibly a hundred degrees colder. As much as a hundred

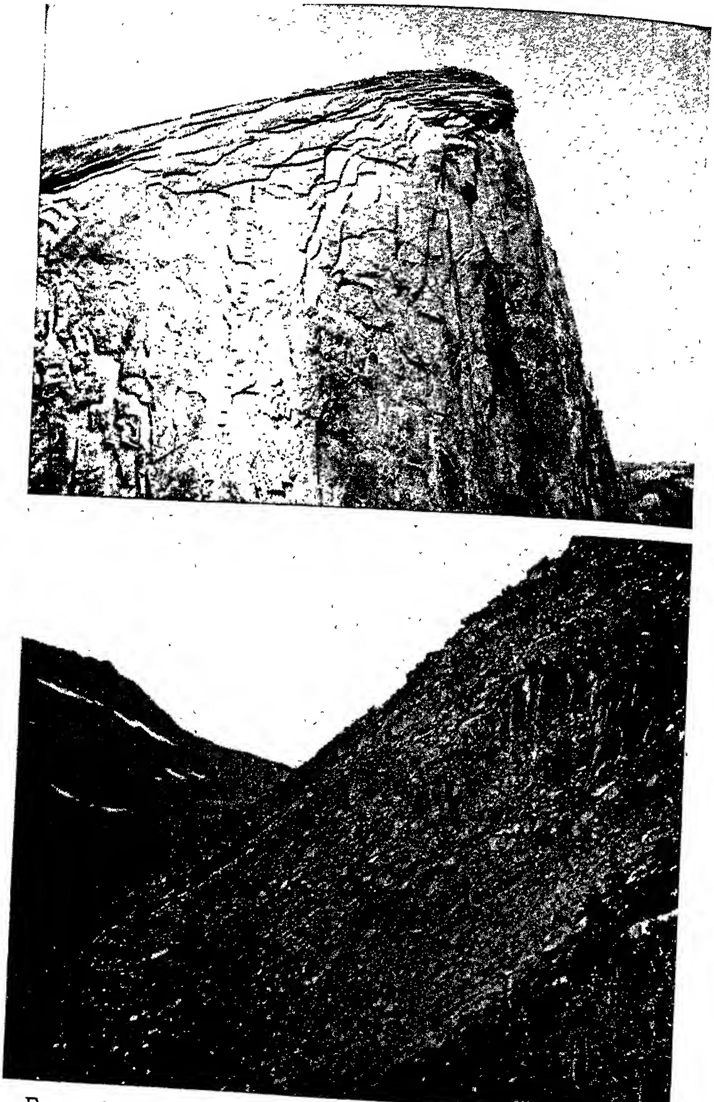


Figure 64. Spalling, or exfoliation, of granite in Yosemite National Park (above) and products of rock weathering in Glacier Park, Montana (below). (Courtesy William J. Miller and D. Van Nostrand Company, Inc.)

pounds or more may break loose at night with a report audible in the stillness for a quarter of a mile. A dull dark rock is both a better absorber and a better radiator of heat than one that is light-hued and polished. Clambering over a rocky hill one can pick out the rocks that will spall most rapidly. Aridity promotes this process, both by discouraging vegetation which would shade the rocks and by promoting relatively great changes of temperature from noon to midnight. The angle of exposure is also important. A rock presenting its surface broadside to the sun will spall more rapidly than one which receives the sunlight at a glancing angle. In the northern hemisphere one sometimes finds hills on whose southern slopes the rocks are breaking up much more actively than those facing the north. In the southern hemisphere, rocks facing partly north would, in general, be the more vulnerable.

The fragments that break off under spalling are of course more readily transported by wind and rain—but differential expansion has not finished with them! Superficial spalling is now greatly retarded; for the fragments lie in thin sheets and the low thermal conductivity is not as effective in preventing uniform heating as in the parent rock. But the granite is a mixture of crystals of many different compounds, and not only do the different kinds of crystals expand different amounts under equal heating, but even a given crystal has different expansibilities in one direction than in another! Perhaps we had better examine this mass of granite more closely.

Granite is one of the *igneous* rocks; that is, it was formed by the solidification of molten rock probably fairly deep in the earth. It may be contrasted with rocks of the *sedimentary* type; for example, sandstone, clay, limestone, shale, peat, coal, salt and gypsum. Even the unaided eye can see that this igneous rock, granite, con-

tains different materials mixed together. Closer examination reveals a mass of interlocked crystals which formed when the molten mass solidified. Crystals of many minerals are present; the predominating kinds are feldspar, quartz and those of a type called ferromagnesians. Feldspar and quartz are light in color, but the rock may be dark gray, or green-gray, or even flesh-tinted. The ferromagnesians, which are compounds of iron, are largely responsible for the coloring. The chemical-minded, recalling our account of the composition of the earth's crust in Chapter 13, will not be surprised to learn that oxygen and silicon are the principal constituents of granite. Eight elements constitute 98 percent of the earth's crust. In order of decreasing abundance, these eight are: oxygen, silicon, aluminum, iron, calcium, sodium, potassium and magnesium. All these elements are present in granite, most of them in rather complex compounds. *Quartz* is perhaps the simplest compound there; it is silicon dioxide, SiO_2 — the same as the sand that we studied in considering the manufacture of glass. The *feldspars,* like quartz, occur in great abundance. These are silicates formed when oxides of certain metals combine with silicon dioxide. Two very plentiful feldspars are sodium-aluminum silicate ($NaAlSi_3O_8$) and potassium-aluminum silicate ($KAlSi_3O_8$). Another is calcium-aluminum silicate. The *ferromagnesian* minerals present in our sample of granite are compounds of oxides of iron, magnesium and silicon, mainly, with aluminum oxide and calcium oxide often entering into the combination.

Granite is well known for its durability; but the fact that it is not only a *mixture,* but a mixture of different kinds of *crystals,* makes it susceptible to a rather subtle form of this insidious disease called differential expansion. To put the story in a nutshell, if the crystals fit together in the rock at one temperature, they cannot fit at another temperature without suffering severe stresses. Just as the

fit of the pipestem in a smoking pipe varies with temperature—the result in part of different expansibilities—so the fit of the interlocking crystals in the granite tends to vary as the rock warms and cools. Without stopping to examine the data for all the minerals in the block of granite, we can see one reason for this result by comparing one of the ingredients, quartz, with the average of the whole. In Chapter 13 we noted a useful result of the exceedingly small expansibility of fused quartz: dishes made of it can be drastically heated or cooled without breaking, as glass would. But that was specially manufactured *fused* quartz, not the crystalline form! The average linear expansion of *crystal* quartz is 28 percent greater than the average expansion of the whole mass of granite. Hence, on the average, an embedded crystal of quartz tries to expand more than its neighbor-crystals when the rock grows warm, and when cooling sets in it tends to shrink away from them. The continual repetition of this straining gradually loosens individual crystals throughout the parts that are heated and cooled, and gradually—Oh, very slowly!—the rock crumbles.

One might think that large expansions and contractions would be required—but on second thought it becomes clear that to separate two portions of a bit of granite by a ten-thousandth of an inch is to separate them as surely as if they had been pulled a mile apart. The actual expansion is small (a slab of granite five feet long would need to be made 125 degrees centigrade warmer to lengthen a full sixteenth of an inch)—but the differential expansion and contraction exist none the less. Even a slight difference of expansions is important whenever fitting is involved. Until a cheaper substitute was developed, platinum wires were used for the connections to be sealed into the glass bulbs of incandescent lamps, because a wire that did not have the same expansibility as the glass broke away from it on cooling.

A simple experiment to illustrate forces caused by contraction can easily be tried. Put a teaspoonful of hot gelatine glue of good quality on a clean glass plate, and dry it slowly in the oven. On drying and contracting, the glue pulls some glass bodily out of the plate. The cause of contraction in this experiment is not the same as that in the granite—but adhesion and cohesion are involved, and these resisting forces, together with actual interlocking of crystals, are present in the granite. Here we saw the adhesive force of the glue holding fast while the cohesion of the solid glass gave way under the pull of the contracting glue.

We have stressed the geological results of changes of temperature partly because they are important factors in the preparation of massive rock for transportation by wind and rain, and partly because they help us to acquire that intimate way of looking at rocks which is one of the geologist's principal tools. Even so, we have not quite finished the story of differential expansion. Not only do the embedded crystals of different compounds expand unequally, but a given crystal possesses different expansibilities in different directions. If you cut a quartz crystal in two with a special saw and then look at one of the sections laid bare by the cut, you find a symmetrical figure bounded by six straight lines. The whole crystal forms a six-sided prism capped at each end with a pointed six-sided pyramid. The geologist with his microscope identifies minerals by their crystal form. In addition to their beautifully symmetrical shapes, all crystals manifest different properties—optical, mechanical, thermal, electrical—in different directions. For example, if one makes a tiny windowpane by sawing out a thin slice of our transparent quartz crystal, everything appears double through it except along one line of sight. This line is the axis of the crystal—and the important fact to be noticed here is that if the quartz crystal is heated, its expansibility is found to be

68 percent greater in the direction at right angles to its axis than along the axis.

Crystals of other compounds behave somewhat similarly. Clearly, when a crystal is heated or cooled, its shape (or, strictly

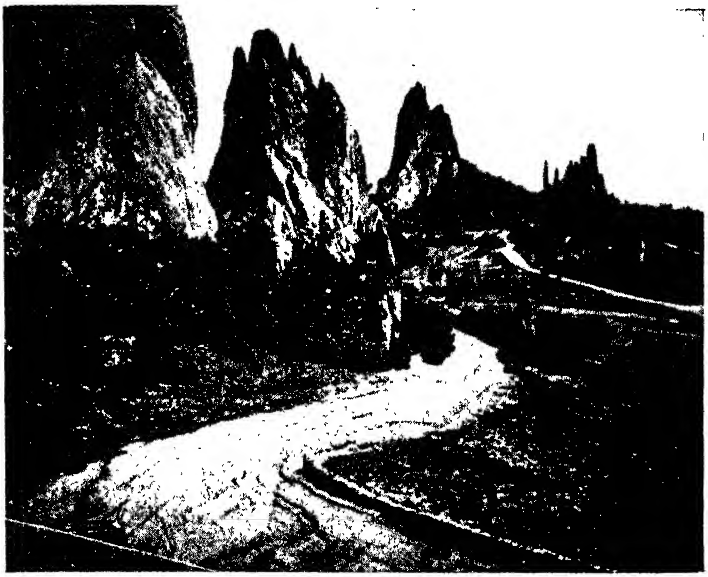


FIGURE 65. Effects of weathering and erosion of red sandstone, Garden of the Gods, Colorado. (Photographed by William J. Miller.)

speaking, its relative dimensions — the thickness in proportion to the length, for example) changes — and if the dimensions of the cavity in which it fits do not change correspondingly, stresses are produced. Thus we see a third lever which temperature wields on our block of granite to pry it apart — and we note in conclusion that the latter two of the three must operate even more effectively on the pieces broken off by the surface spalling than on the main body of the rock. Hence even if no other actions occurred, the

ultimate end of the granite would be pulverization. Like a gathering torn by internal dissension, the rock tears itself apart—and may one day help to soften the tread of a bather at the beach.

If we gave as much time to every important geological process

FIGURE 66. Unequal weathering left this rock remarkably balanced near La Veta, Colorado. (U. S. Forest Service.)

as we have to these temperature effects, we should have a whole book of geology on our hands. But we have been seeking an outlook as well as a few facts to add to our repertoire. Now we must hurry on. The abrading action of wind and the dissolving action of rain are perhaps so nearly obvious that we need not dwell on them in a short account of the natural processes which prepare

the rocks for transportation. Wind armed with sharp-toothed abrasive grains of hard minerals is a natural sandblast, scouring the rocks and wearing them down. Rain gradually dissolves the more soluble minerals out of the surface rock, leaving tiny pits in the

FIGURE 67. A granite boulder split by a growing tree in Custer County, South Dakota. (U. S. Forest Service.)

surface which facilitate further action by rain, wind and sun. Wind blows, and rain washes away, the protecting mantle of debris (*mantle* rock) formed by spalling, exposing the underlying massive rock anew to the attack of its natural enemies. Like the scouring off of the first layer of oxide to be formed on an aluminum pan, the removal of the products of atmospheric action subjects the parent body to further assaults. Other actions go on relentlessly.

Living agents, both plants and animals, rework the rocky debris, loosening it further. Roots burrowing into crevices sometimes split the massive rock. The stroller coming across cracks and bulges in the paved sidewalks of tree-lined avenues may judge how great a force a thickening tree root can exert. Water freezing in cavities expands and may crack the rock as readily as it bursts a stout iron bomb in the familiar laboratory experiment. These readily appreciated actions we merely mention, and pass on. But underfoot, day and night, there is going on a less obvious process which we cannot dismiss so quickly. We conclude our brief treatment of the preparation of the rocks for transportation with a short description of chemical weathering.

Underground Water and Chemical Weathering

The weathering actions which have concerned us thus far occur at the surface of the earth. We have considered some of the processes by which massive rock is converted into the raw material of soil. Now we must look down into the regions where hidden water percolates through the rocks. We are trying to avoid confusing the actions which break down rocks, with those which transport the products of the disintegration; but we cannot leave moving water out of the story of chemical weathering. Rain seeping into the earth is not only a chemical agent itself, but provides the means by which the reagents for certain chemical transformations of great importance to man are brought together.

The existence of springs, geysers and wells, and the difficulties encountered in draining swamps, afford ample evidence to all of the presence of underground water. In low-lying swampy areas the ground water reaches the surface. In some places one may need to dig only a few feet to strike water; in others, hundreds of

feet. Elsewhere one may strike no water even if he digs to the maximum depths yet touched by the driller's art. Small rivers that emerge from the ground, or disappear into it, are not unknown. Digging to make room for the foundations of buildings sometimes presents problems: continual pumping may be needed to remove the ground water. The *water table* is important everywhere to builders, growers, miners, and well-diggers; it is the upper limit of the layer of ground that is saturated with water.

Water finds some rocks highly permeable, or porous; others impermeable. Highly permeable rocks may be so porous that they can hold as much as thirty percent of their own volume of water. Layers of impermeable rock alternate with porous strata in many regions. An impermeable layer may lie above a water-filled stratum, serving as a roof to confine the slow currents of ground water. If this impermeable layer curves downward, the ground water is forced deeper. The deeper the downward dip, the greater the pressure at the bottom. By drilling a hole through the impermeable layer of rock at or near the bottom of the curve, the householder can release the imprisoned water and provide himself with an *artesian well,* from which water may at first flow like a fountain. Chicago was for many years served by artesian water, much of which came from great beds of sandstone lying at greater heights in Wisconsin. But water percolates slowly through the small pores of rocks. The demand exceeded the supply, and gradually the underground rock was drained over a large area. Replenishment goes on too slowly to care for a great city of Chicago's present size. But many towns today find artesian wells adequate for all their demands. How deep the water penetrates into the earth's crust is not known. Estimates as large as twelve miles have been made; but the distribution of ground water is very irregular, and in certain areas the upper portions of mine shafts

must be sealed against water although the lower depths of the same mine are dry as dust.

If all the underground water were distributed uniformly over the world, the thickness of the layer would doubtless be several hundred feet. This great unseen ocean is a chemical bath. Sparsely concentrated in its waters, in very dilute solution but aggregating billions of tons, are active chemicals derived from the atmosphere and from the ground through which the water seeps. The oxygen and carbon dioxide dissolved out of the atmosphere by rain are especially important.

At first glance one may wonder why our story of chemical weathering stresses underground water rather than the atmospheric oxygen which makes contact everywhere with surface materials. Again and again in our pages we have come upon this highly active component of the atmosphere. No other element is distributed so widely among the compounds which form the earth's crust. If, in a super-chemical laboratory, we could recover all the oxygen which is combined with other elements in the outer shell of the earth, we should find that the weight of the oxygen thus reclaimed nearly equaled the combined weights of all the other elements. Oxygen runs through any comprehensive list of large-quantity minerals like the recurring theme of a symphony. Sand is silicon dioxide; limestone and marble are calcium carbonate ($CaCO_3$); pure clay is $H_4Al_2Si_2O_9$; the great beds of iron ore distributed through the world contain not iron, but oxides of iron; representative feldspars, which contribute a large share of the bulk of granite and other igneous rocks, contain eight atoms of oxygen in every molecule.

Oxidation is of course going on all over the world, especially in conjunction with plant and animal life and with the waste materials that result from the processes of life. A number of these

actions were dealt with in our study of the energizing and body-building of plants and animals, in Chapter 12. The geologist is interested in these oxidations—but he is especially interested in changes of the oxygen-content of minerals which already are compounds of oxygen. He begins his study with an inventory of raw materials in most of whose molecules oxygen is already firmly locked. Who knows when, or how, or where the raw element silicon, for example, combined with free oxygen to form the silicon dioxide out of which the sands of the world are made? An imaginary earth made up of virgin elements, exposing great beds of free silicon to the heavens—and free aluminum, free iron, free calcium, magnesium, potassium and sodium—would be the scene of appallingly violent activity for a while if it suddenly acquired an atmosphere containing oxygen and that oxide of hydrogen called water. The logical mind seeks origins; but it will be the astronomer, if anybody, who traces minerals back to a time when virgin elements were combining with virgin elements in the heavens to form the stuff of planets, or perhaps, going farther, when protons and electrons were joining forces to form the elements themselves. But whence came the electrons and the protons? . . . What the geologist can do is to trace many changes of chemical composition in the earth's crust—and of these we select several important examples.

Going back for our first example to that massive block of granite which served us in our account of the work of differential expansion, we recall that one of its principal components is feldspar. What will the dissolved carbon dioxide carried by the underground water do to a buried mass of feldspar? This plentiful mineral is a compound of silicon, oxygen, aluminum, and one or more of the elements sodium, potassium and calcium. If sodium, the formula is $NaAlSi_3O_8$. If we look up the formula of pure clay

(kaolin) in our earlier section on the manufacture of brick, porcelain and other pottery, we find it to be $H_4Al_2Si_2O_9$. This resembles the formula of the feldspar so closely that to turn feldspar into clay all that is needed is to substitute hydrogen for sodium and change the proportions of silicon and oxygen slightly. The water that carries the carbon dioxide supplies the hydrogen. The equation shows the result at a glance:

$$2NaAlSi_3O_8 + 2H_2O + CO_2 \rightarrow H_4Al_2Si_2O_9 + 4SiO_2 + Na_2CO_3$$

The action progresses slowly but surely, and the feldspar is said to be chemically weathered. On the left we recognize the feldspar, water and carbon dioxide. On the right, as the products of the reaction, we find clay (kaolin), silicon dioxide and sodium carbonate. This reaction, together with the corresponding reactions for the other varieties of feldspar, provides the world's pure *clay*. Common clay consists of pure clay (kaolin) mixed with mica, silicon dioxide, iron oxide and organic matter. The form in which the *silicon dioxide* may eventually be found depends on what happens to it later. This ubiquitous mineral is familiar in many guises—in great quantities as sand, crystal quartz, and infusorial earth, and less abundantly as agate, opal, amethyst, jasper, flint and other forms, many colored by traces of impurities. The *sodium carbonate* serves two important functions: it renders the ground water strongly alkaline, thereby increasing its ability to dissolve silicon dioxide and deposit it elsewhere to cement grains of other minerals into massive rocks; and it is itself a valuable raw material used, as we saw in Chapter 13, in the manufacture of glass. If the feldspar being subjected to this action contains potassium instead of sodium, potassium carbonate is formed; if of the calcium variety, *calcium carbonate*. This calcium compound occurs abundantly as limestone, marble, calcite, chalk, and in sea shells, coral

reefs and other deposits of the skeletal features of marine life. In Chapter 13 we saw tons of limestone disappearing into the great tanks of the glass-makers and into the blast furnaces where iron is won from the ore.

Limestone formed by the weathering of feldspar or otherwise is far less resistant to the action of ground water than is the feldspar itself. In pure water limestone is practically insoluble, a mere fourteen grams dissolving in a million grams of water, or half an ounce in a ton; but if the water carries with it carbon dioxide which it has dissolved out of the atmosphere the solubility of the limestone *seems* to increase by as much as a hundred-fold because of a chemical reaction which takes place. Strictly speaking, the apparent increase of solubility is the result of a chemical action. One molecule each of limestone ($CaCO_3$), water (H_2O) and carbon dioxide (CO_2) unite to form one molecule of *calcium bicarbonate,* whose formula, containing all the atoms just indicated, is written $Ca(HCO_3)_2$. The calcium bicarbonate produced by this action is one of the impurities which makes water *hard* in limestone regions — but more to the point, for our present purpose, it is approximately forty times as soluble in water as the original limestone. Hence the limestone slowly disappears, and in its place calcium bicarbonate is carried away by the circulating ground water. The action is really two-fold: water and carbon dioxide uniting to form carbonic acid, and this attacking the limestone. Who has not seen the sinkholes encountered so frequently in limestone areas — places where the surface ground has finally fallen into a cave eaten out in the limestone beneath it by this chemical action? If a building stands on the site, it goes, too, the victim of this insidious chemical sapper.

Occasionally the tourist comes upon road signs directing him to great caves ornamented with beautiful stalactites and stalagmites

—"icicles" of limestone. These are formed by the same action that makes the sinkholes. Walking through the connecting caverns of such a cave, one after another in seemingly endless succession, one comes to appreciate the possibilities of chemical weather-

FIGURE 68. Stalactites and stalagmites at Oregon Caves, Oregon. (U. S. Forest Service.)

ing. To understand how the stalactites and stalagmites were formed, merely note that the reaction which removes the limestone is reversible. The dissolved calcium bicarbonate dripping down from the ceiling of the cavern gives up water and carbon dioxide in the open air, producing limestone again. Like an icicle growing longer and thicker as water trickling down the part already formed freezes, the stalactite grows down from the ceiling; while the excess dissolved calcium bicarbonate drips down to the floor and

there undergoes the same action of reversal, freeing limestone to form the stalagmites that rise from the floor. In Mammoth Cave in Kentucky the enthusiastic explorer can build up a mileage running into scores without counting any underground thoroughfare twice. Luray Caverns in Virginia, Carlsbad Cavern in New Mexico, the Cave of the Winds in South Dakota, and numerous other subterranean mansions bear witness to the work of underground water.

The full story of chemical weathering would be a long one; we conclude with an example involving dissolved oxygen carried down by the ground water. The most important iron ore mined in the United States is hematite (ferric oxide Fe_2O_3). This red compound is responsible for the red coloring of many soils. Another common form in which iron occurs in the earth's crust is magnetite (Fe_3O_4). The magnetite, despite its four atoms of oxygen per molecule, actually contains less oxygen in proportion to iron than does the ferric oxide. Counting atoms shows this at a glance. Either six molecules of Fe_2O_3, or four of Fe_3O_4, would furnish twelve atoms of iron; but the numbers of atoms of oxygen would be eighteen and sixteen, respectively. Hence iron is more highly oxidized in the form Fe_2O_3 — and one of the results accomplished by oxygen dissolved in ground water is to transform magnetite into the more highly oxidized ore. The action is accompanied by an increase of volume which helps to disrupt the minerals in which the iron ore is embedded. Of course, the added oxygen must be removed when the ore is refined, so this example of weathering is not necessarily an advantage to man — but other weathering processes which may occur in conjunction with the addition of oxygen enrich the bed of ore by removing some of the valueless materials.

These illustrations of the chemical and dissolving action of un-

derground water suggest the answers to many questions. Surely the reader will now answer for himself the question, " Why is the sea salt? " The transformation of portions of the rocky crust into soluble compounds which may either drain into rivers and hence reach the sea, or be deposited in underground cavities or in exposed basins where the water containing the dissolved compounds evaporates and leaves them behind, explains many features of the world that are known to all. To recover salt and other substances by evaporating some ocean water in a pan; to hang a thread in a hot saturated solution of cane sugar and watch the crystals of rock candy form as the solution cools; to fill the pores of a rough mineral specimen with powdered sulphur and then dissolve the sulphur out with carbon disulphide; to cleanse some mercury by bubbling air through it to oxidize the impurities and bring them to the surface as a readily removable scum; perhaps to bubble one's breath through a solution of calcium hydroxide (limewater) until the carbon dioxide in the breath produces a cloudy precipitate of calcium carbonate — these and many other simple experiments that might be performed will suggest, not necessarily the actual results, but the *kinds* of results that can accompany the physical and chemical processes which do occur in the regions where hidden waters flow.

Chemical weathering may remove the more soluble minerals. The clay formed by the weathering of feldspar may be deposited in beds of great commercial value, or it may become mixed with sand and other minerals to form infertile soil. The sites of future quarries are staked out and filled in; metal-bearing ores of certain kinds may be concentrated by a chemical weeding-out of extraneous material which would reduce their value.

And soil is made. Rock broken into fragments by differential expansion is still rock, not soil; but the chemical action of water,

oxygen, carbon dioxide and small concentrations of other chemicals gradually weathers the rocky mantle into a form in which vegetation can gain a foothold. Once organic life has begun to flourish in the debris, the transformation into soil can be completed. Soil bacteria; roots; burrowing; the decomposition of vegetable mould and the excrements and carcasses of animals of all kinds, especially the worms and other tiny creatures — the physical, chemical, and biochemical actions of these agencies complete the work. We have traced in exceedingly rapid outline the transition from rock to soil — but the reader's own observation and reflection may perhaps help us by filling in some of the gaps.

Rivers Young and Old

Once rocks have weathered, soil formed, vegetation gained a foothold, what happens to the soil? Wind and rain, which helped to weather the rocks, now try their hand at transporting the products. Somewhere in a high shoreland the rain water running down a steep declivity into the sea finds what may be at first little more than a scratch, a linear depression neither broad nor deep enough to be dignified by the name of gully — an inconspicuous furrow such as might form in a farmer's backyard where rain drips from a corner of the barn roof. The running water concentrates; the furrow wears into a gully, the gully into a ravine, the ravine into a valley. Who knows what the future may hold? Every schoolchild a potential president, every brook a potential river! The mortality is high in both cases — but here and there aid comes to a chosen few. Other trickles divert their courses into the embryo river channel. The lone enterprise becomes a cooperative project. Tributary trickles turn into brooks, rivulets, streams. Meanwhile, the increasing rush of water deepens the

main channel, cuts back the banks, broadens the area that feeds it. A river has been born.

Young streams leap and foam on their exultant way to the sea; old streams wind slowly, sedately. The river is born at the seashore and cuts its bed back into the highlands. Leaping from ledge to ledge in narrow torrents it carves its channel deeper — and the deeper the channel, the greater the tendency of water to rush down from the bordering heights. Waterfalls are numerous. Rocks are dislodged and carried along, the bed and banks scoured. Now the valley at the mouth has grown wider and more nearly level. An ever-increasing mass of debris is deposited near the mouth and begins to form a smooth expanse of fertile delta land. Farther and farther back into the continent the natural surgery of moving water carves the watercourse. The drainage basin grows as the head of the stream retreats from its outlet. The foraging stream taps the waters of small lakes hitherto trapped in high-lying depressions and appropriates their beds. It may invade the drainage areas of competing streams and capture, or *behead* them, diverting their headwaters to feed itself. Finally, stopped by a divide high in the mountains, or encountering a lake too large to appropriate, the now mighty river ceases to lengthen and proceeds to consolidate its position.

The continuing wear and tear of running water flattens a broad valley. Local restrictions that induced high velocity when the stream was young, are gradually removed. Part of the load carried by the current consists of rocks rolled along the bed; many of these are deposited in holes previously gouged out at the feet of the waterfalls that characterized the stream's youthful zest. The bed of the river smoothens, the pace steadies. The stream, now growing old, begins to meander. Across the wide flood plain it swings from one valley wall to the other. Centrifugal force comes into

play at the bends. The moving water, concentrated in force against the concave shore at the outside of the bend, wears it away; while directly across the river, at the inside of the bend, debris is deposited in the slower, shallow water. Scouring and filling, scouring and filling, the stream slowly pushes the bends both downstream and sidewise. Thus the channel itself undulates slowly as the water, now yellow with its heavy burden of mud, weaves onward. The valley plains along the lower reaches of the stream become nearly level with the sea, and rich with alluvial deposits — ripe for agriculture and ripe for floods.

What we have now to consider is the work done year after year by an old river, a river like the Mississippi. The Mississippi is only one of the great rivers which are at work changing the surface of the earth, but it is one of the greatest. From Lake Itasca in northern Minnesota it runs 2,486 miles to the Gulf. The Nile, the Amazon, the Ob, the Yangtze, the Amur, the Congo, the Lena and six other rivers, including one of its own tributaries, the Missouri, exceed the Mississippi in length; but only three — the Amazon, the Congo, and the Nile — surpass it in area of drainage basin. Including its fifty-four navigable tributaries, numbering among them such great rivers as the Missouri, the Arkansas, the Red River of the South, and the Ohio, the Mississippi River system provides a total of 13,912 navigable miles. If we pause for a quick picture of what the Mississippi is doing we can multiply the effects many-fold and know what rivers are doing to the earth.

The Mississippi River system draws its water from 1,290,000 square miles. This is 43.5 percent of the whole area of the forty-eight states. On these 1,290,000 square miles of territory there falls annually three thousand billion tons of rain. If one could enclose the state of Indiana and make it water-tight, then concentrate behind the wall all the rain that now falls in the Mississippi's basin,

five months would suffice to form a state-wide sea capable of floating the world's shipping, including all the navies and the Normandie and the Queen Mary. The average annual rainfall in the Mississippi drainage area is well over two million tons per square mile — approximately 3600 tons per acre. A thunderstorm may pour several hundred tons of water on an acre in a single hour. Some of this water is converted into the bodily substance of plants and animals; more is evaporated; and the remainder — a large fraction of the whole — is carried off by the Mississippi and its tributaries. In many localities some of the water may remain behind to raise the level of the ground water; but the average water table is decreasing year after year over much of the area in question, hence the temporary diversion to ground water can hardly decrease the average annual run-off in this region.

The tremendous volume of water running off carries part of the land with it. Some soil is washed away bodily; this is erosion. The soil that remains is partially *leached:* it parts with its soluble compounds under the dissolving action of the water that percolates through it. Both actions wear down the surface and reduce fertility. The extent of the damage can hardly be appreciated unless one has surveyed the gullied ruins of a once-fertile farm. It is estimated that the Mississippi River transports every year approximately four hundred million tons of mud, sand and gravel. A century of accumulation at this rate would supply material for a cone-shaped mountain five miles high on a base of five square miles. And a thousand years? A million?

Clearly, the highlands are growing lighter, the sea-bottom heavier. If you fill a bathtub with marbles, set a round-bottomed mixing bowl on top and start loading the bowl with weights, eventually it sinks. The marbles slip laterally beneath it, and somewhere else at the side the level of the marbles rises. So with

the earth, if the widely held view of isostasy is true. The equilibrium of pressure is upset by the steady transfer of highlands to the sea. Sooner or later rock will fold, heavy lowlands will sink, light ground will rise, new mountains will be born to begin the cycle anew. But we are getting ahead of our river. The Mississippi is still here, carrying away the fertile soil at a rate which, averaged over the entire 1,290,000 miles of its drainage basin, amounts to an annual loss of about three hundred tons per square mile, or half a ton per acre. Some areas suffer a smaller loss, some many times as great.

About two-thirds of this great load of geological freight is carried in suspension in the solid form. Slightly more than a quarter is dissolved material; and the small remaining fraction, a few percent only, is rolled along the river bed. All these losses are serious, especially so the matter carried in solution. The soluble compounds in the soil are those that are immediately available to plants, and their loss without adequate replacement involves ruin, soon or late, for agriculture. The removal of solids in large quantities requires a reasonably rapid flow; but even a slow percolation of water through the porous topsoil can ultimately drain it of its rich soluble elements of fertility. The selective action of solution is one of the reasons why those four hundred million tons carried away annually by the Mississippi are the richest part of our natural heritage.

The main outlines of the Mississippi drainage area were carved with no help from man. What is happening in great portions of that valley now, one can judge by the newspaper stories of flood, drought, dust storms, abandoned farms and projects of resettlement. In the natural state such a basin, after being worn low and nearly level, develops an external equilibrium. Matted vegetation in the lowlands holds water and retards erosion. Higher,

forests shed their leaves, forming a thick covering mantle which promotes the maintenance of the water table underground. The leaves and other debris prevent the rainfall from running off in sheets, giving it time to settle into the soil; and by filtering out the mud which would clog the pores of the soil, promote seepage into the underlying strata. The river bed near the mouth is gradually built up by silt dropped by the slackening current before the water reaches the sea, and the higher lands at the head continue to be worn lower, but more slowly. Thus the gradient of the stream is rendered more gradual, the velocity decreases, sediment is deposited in the channel, the stream meanders more, swamps and lakes form in the flood basin. It is still a great river, but the annual losses of ground due to erosion and leaching are nearly balanced by the decomposition of natural debris, which makes fertile soil. Such is the condition of this old river before man arrives on the scene.

Now settlers arrive en masse. The situation changes. Lands are cleared of forests; grass lands are cropped close by grazing herds. The protecting mantle of natural debris diminishes. Soil harried with plows falls easy victim to erosive and leaching action. The surface run-off of water increases, and with it erosion. Less water sinks into the natural storehouse underground. In the north temperate regions of the basin snow melts more rapidly where the forests that formerly provided shelter in the spring have been cut down. A greater volume of water from melting snow (an important source of moisture in half of the United States) is produced in a given time, and a larger fraction of it runs off instead of sinking underground. What does run off runs faster than formerly, because of the lack of covering debris once furnished by the forests. So floods are more frequent, and more severe — and at the same time the amount of water stored underground dimin-

ishes. Many still look on forests as merely potential houses, newspapers and furniture, but floods and droughts alike remind us that a tree standing has its uses.

Ever since 1717 artificial levees have been in process of building and extension along the lower portion of the Mississippi River. This shows that deforestation and stripping off the covering mantle farther up the drainage basin are not the sole causes of flooded conditions. The soil is fertile in the flood plain, and man is reluctant to allow the stream all the elbow room that it would normally use in the natural state. In recent years the level of the levee crests has been raised several times. Now one finds a total of 1825 miles of levees averaging twenty-one feet in height. The continuing deposition of sediment raises the river bodily, so to speak, and the upper few inches or few feet, as the case may be, may be likened to an aqueduct confined only by the levees.

And while inhabitants of the flood plain cherish their levees, droughts increase in severity in other parts of the river's drainage basin. Flood and drought go hand in hand. The water rushing in sheets over the hard, well-washed surface of land that has been stripped of its cover, tends to produce floods in time of heavy rainfall or rapid melting of the winter's accumulation of snow; and in rushing off so rapidly, it does not tarry long to sink into the ground or to evaporate into the air. In a great rectangle formed by four northwestern states, the level of the underground water has dropped eight to seventeen feet since man began large-scale operations there. In a few regions the water table has dropped an average of two feet a year for twenty years. The western parts of the drainage basin have suffered heavily. Wells run dry; aridity of the soil increases; the protecting mantle of vegetation thins still more; a desert may be in the making. The dust storms are too recent to need elaboration here. The Mississippi's yearly freight

of four hundred million tons of land seems large; but it is estimated that approximately three-fourths that many tons of topsoil blew away in a single day when the dust storms blew fiercest in the Great Plains area in the spring of 1934. Whole farms, at least all that was useful of them, were carried from one state to another with no transfer of title to be registered with the county clerk, and some of that land now rests at the bottom of the Atlantic Ocean two thousand miles away.

So we end our discussion of the transportation of weathered rock on a note of calamity. But the conditions which encourage floods, droughts and dust storms are at least partially understood, and with understanding and dissemination of the truth, measures of correction can be undertaken. Our task in this section was to trace the evolution of a stream, and to show the work that it does in transporting the products of weathering. Glaciers, too, and volcanoes, help in the work of changing the earth's surface and moving materials from one place to another; but their action is so intimately bound up with the geological history of the earth that the start of a new chapter seems to be in order.

Chapter 17

THE HISTORY OF THE EARTH

If the work of weathering of all sorts, with the attendant erosion and deposition, were all that the geologist had to tell us, the history of the earth, like the history of energy on its unbroken path of degradation, would be a story with a misplaced climax. Contrary to the dramatist's rules, the climax would occur at the beginning, when the matter now composing the earth was separated from the superficial layers of the sun — and from that stirring high point the tale would meander downward like an ancient stream. The high places of earth would be degraded, the low ones filled — and the last mariner, circumnavigating the globe in any path he chose, would find no harbor in the unbroken wastes though he sailed his ship until he died of ennui. For twenty or twenty-five thousand years — the years since the last great ice sheet retreated to Canada from points south of the present Great Lakes — the plunging waters of Niagara Falls have carved their rocky escarpment backward at an average rate of approximately five feet a year. Not only at Niagara and in the Mississippi Valley, but elsewhere at a prodigious rate, North America is being carried to the sea. The annual toll levied at present by all the rivers of the United States is considerably more than 800,000,000 tons. How long can North America last without some help? The continent, now at an average height of approximately two thousand feet above sea level, is being lowered at an average rate of one foot every nine thousand years. The rate varies with the centuries as the grade changes under erosion already completed. At the present rate, if no counter-

vailing upbuilding occurred, eighteen million years would suffice to let the waters of the Atlantic and Pacific join hands across the continent. Actually, eighteen million years is not enough; for the rate of erosion would diminish as the plains broadened and approached sea level — but doubling, tripling, or quadrupling that period would still leave us a mere fragment of geological time.

Eras, Periods and Epochs

Referring back to Chapter 4, in which we found how to measure the age of the earth, and again to Chapter 10, where radioactive transformations were dealt with more fully, we remind ourselves that the ages of certain rocks can be measured by the exact methods of physics and chemistry. The exploding atoms of uranium, thorium and their progeny silently tick off the time as the ages pass over the more durable and better-protected rocks. The number of explosions per second is not affected by any treatment to which the rock may be subjected, and the explosions leave records. Thus old rocks can be distinguished from young, ages determined — and the oldest accessible to man made to reveal their antiquity. The earth, as we saw once before, is at least two billion years old, probably older. The fragment of time in which, at the present rate of erosion, North America would be worn down to the sea, could be expanded six-fold and still be no more than one-twentieth of the known duration of the earth. Mountains are transitory, but the downward degradation is punctuated by rejuvenating processes. Climaxes of upbuilding occur. The time-chart of the earth shows both ups and downs, as a good drama should.

So we come to *C-m-p-p-a* — a word not to be found in any dictionary. *Cmppa* looks like something out of a foreign correspondent's nightmare, but is merely the initials of the eras that

the geologist knows. *Modern, medieval* and *ancient* would not subdivide two billion years sufficiently; and besides, they might be confused with the historian's periods of human affairs. Beginning with the *Cenozoic* — the era which started with the first low mam-

FIGURE 69. Stratification of sandstone. The thin dark layers are beds of shale. (Photographed by William J. Miller.)

mals and progressed to man — and looking back from this vantage point, we find, in order, the following eras: *Cenozoic, Mesozoic, Paleozoic, Proterozoic,* and *Archeozoic.* The words themselves should be memorized by anyone who intends to read the literature of geology — and *cmppa* may help to fix their order. Fortunately, the sequence of *Paleozoic* and *Proterozoic* in the list is the same as the alphabetical order, so the two "p's" in our trumped-up word sort themselves out. The "a" at the end might also be doubled, for some geologists add still another era, the *Azoic,* to allow for the

additional billion years or so which may have elapsed between the birth of the earth from the sun and the formation of the earliest Archeozoic deposits of sediments. But let us confine our attention to the five great eras about which something is known. We shall

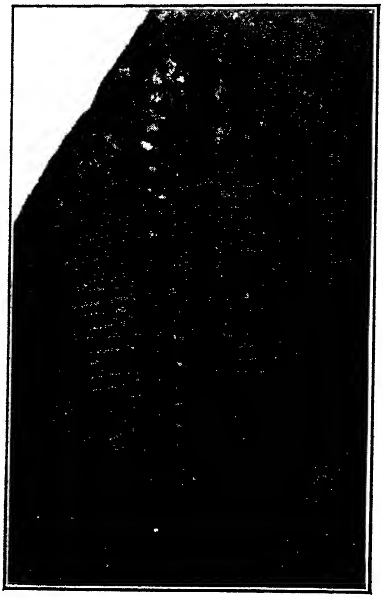


FIGURE 70. A fossil sea-animal (trilobite) found 9000 feet above sea level in the Rocky Mountains. (Courtesy William J. Miller.)

have enough on our hands, more than can be epitomized in the short space that remains at our disposal.

In this business of looking back into time, the astronomer has one advantage over the geologist. Availing himself, perforce, of the slowness of nature's swiftest communication, the astronomer (and everybody else) sees the moon as it was a second and a fraction ago; the sun as it was eight minutes ago; Sirius, nearly nine years; Vega, 26 years; Polaris, four centuries; Rigel, as it was when it launched

its rays at Jeanne d'Arc. He sees the globular cluster of a million stars in Hercules in a state that existed three hundred centuries ago, and the Great Nebula in Andromeda as it was 900,000 years ago. A long time, this last—but not quite half the duration of the Pleistocene *epoch* of the Quaternary *period* of the most recent *era,* the Cenozoic! And in this relatively short epoch of a period of an era, an epoch which began soon after horses and elephants had assumed a nearly modern form and which culminated in Cro-Magnon man, there were four great ages of ice. One epoch of the six which the geologist recognizes in the Cenozoic era!—yet there was time for large portions of the globe to be covered, not once but four times, with ice sheets. These ice sheets, to judge by the debris which they left and by the rising of the land of Canada north of Lake Superior after the pressure was removed, must have been several thousand feet thick. The four glaciations were separated by warmer intervals lasting thousands of years each. Only recently a geologist in New England, painstakingly counting the seasonal banding or lamination (varves) of glacial clay left by the last Pleistocene glacier as it receded from that region, traced the path of the glacier's terminus through a 186-mile retreat which required 4100 years to accomplish. This was a small fraction of *one* retreat—and there were four advances and as many retreats. Intervals each at least ten times as long as man's dated history were sandwiched between the successive glaciations of this short epoch.

What caused these ice ages? Will they come again? There are questions to be answered, and we shall return to them. In a first effort to make the idea of age more real than a number on a page, we have merely dwelt for a moment on characteristic events of an epoch which filled no more than one twenty-fifth of the most recent era, the Cenozoic.

The geologist must read the records as he finds them. He may

not be able to make pronouncements quite as definite as that of Archbishop Ussher of Ireland, who declared in the seventeenth century that the earth was created at nine o'clock in the morning on October 26, 4004 B.C.; but to accept a duration of the earth much shorter than a third of a million times as great as Ussher's figure is to suppose that the mind of man is playing tricks on him. Of course, many mistakes have been made. Witness Professor Johannes Beringer, for example, the early eighteenth century naturalist of Würzburg, who did not discover until after he had published his ill-fated treatise that the haunts where he collected his specimens had been "salted" by his students with spurious fossils and relics of their own manufacture. And as late as 1857 the eminent English naturalist, Philip Gosse, restated the hoax *motif* with new and startling implications. Gosse contended that God himself had put all the fossils into the rocks when He created them, to mislead the weak in faith and prove the constancy of others. All the patient measurements of a thousand eminent geologists could never refute that argument; for, as Sir William Dampier has pointed out, one's memory and records of even his own existence might conceivably be implanted by the same means, with no need of the events themselves.

But if one is to mistrust all human minds, and doubt all ideas save one, he will be going counter to a course that has enriched men's minds, and many pockets as well. In 1910, Finland's richest copper mine was discovered by tracing fragments of ore back along the path of the vanished glacier that had dropped them. To find likely places for oil the geologist traces the ancient shore-lines of continents which have been altered by the diastrophic forces that build mountains; and, having found the likely places, prospects with the seismograph and artificial earth-tremors induced by dynamite, or with a pendulum so sensitive that it adjusts its period

perceptibly to the density of the material above which it swings. Five years after the geophysical methods were introduced in the Gulf Coast region, as many new oil-yielding salt domes had been discovered there as in the preceding thirty years. By similar methods geologists have found where oil is to be expected beneath the floor of the Gulf of Mexico, and it is not beyond the bounds of reason to anticipate that, despite the obvious difficulties, these may some day be tapped to meet the demands of the automotive age. The same geological knowledge that makes us aware of our earth's rich heritage of history finds tangible wealth of many kinds — and it would seem illogical to accept the reality of the wealth and doubt the history that helps to find it.

What a picture the events of the five eras would make if we could telescope them into an hour at the motion picture theater! Some of the events, of course, would be indistinguishable, flashing past so fast that the mind could not take them in. The talking picture projector throws 24 still frames or snapshots on the screen every second, 86,400 frames per hour; and the spectator, availing himself of his own persistence of vision, sees actors and objects go through their paces. What would a one-hour geo-film of the two billion years look like? Every still frame would mark the passage of 23,000 years; every second, more than half a million. The 4100 years during which the New England glacier retreated the 186 miles we mentioned would not be caught. The events since early Neolithic savages began using tools of polished stone would make one frame, a picture to rest for one twenty-fourth of a second on the screen. The advance and retreat of all four of the Pleistocene's great glaciations would flit past in less than four seconds, and of course the sights and sounds of earthquakes and volcanic eruptions, or of mastodons trapped in the California tar pools of the Pleistocene, or of the saber-toothed tigers, wolves and vultures that at-

tempted to feed on them, would not register at all. Glaciers and forests, seas and arid plains, would follow on one another's heels. The earth's crust would rise and fall. Now a valley would be drowned, now a continent. Mountain ranges would pop up, and wear down almost as fast. Picturing oneself on that heaving crust, one might feel the sensations of an oriental potentate tossing and tilting in his palanquin while the bearers quarreled beneath.

Two kinds of geological processes, *diastrophism* and *volcanism,* account for that underground "quarreling" which from time to time remodels the earth's surface. These, together with *glaciation,* must be our principal topics in this chapter. Glaciation, from one point of view, is merely one of the many processes of *gradation,* or wearing down, which we discussed in the preceding chapter; but from the standpoint of climate it merits a category all its own.

But first let us put our motion picture correlation to a sober use. No matter how good the intentions, the imaginative mind occasionally refuses its duty when prodded along a path of visualization that spans years by the millions. There come moments when thousands could be written for millions, or billions for thousands, and the substitution might hardly be noticed. But *relative* durations are not subject to this limitation of the mind. How is the one-hour showing time of our geo-film to be apportioned among the five great eras of the earth? The figures in parentheses give the showing time. We list the eras in order as they recede into the past: *Cenozoic,* 50 million years (1.5 minutes) —*Mesozoic,* 150 million years (4.5 minutes) —*Paleozoic,* 350 million years (10.5 minutes) —*Proterozoic,* 650 million years (19.5 minutes) — *Archeozoic,* 800 million years (24 minutes). Total number of years, two billion; total showing time, sixty minutes. We see that the number of years assigned to an era increases with antiquity. The Archeozoic would make sixteen of the Cenozoic. Possibly

THE GEOLOGIST'S TIME TABLE

Eras	*Periods*	*Epochs*
Cenozoic	Quaternary	Holocene
		Pleistocene
	Tertiary	Pliocene
		Miocene
		Oligocene
		Eocene
Mesozoic	Cretaceous	
	Jurassic	
	Triassic	
Paleozoic	Permian	
	Carboniferous	Pennsylvanian
		Mississippian
	Devonian	
	Silurian	
	Ordovician	
	Cambrian	
Proterozoic	(Subdivisions frequently used in N. A.)	
	Keweenawan	
	Huronian	
	Timiskaming	
Archeozoic	Laurentian	
	Grenville	
	Keewatin	

the geologists of some far-distant day, working without the written records of this or succeeding civilizations, may condense several of our recent eras into one. But who can say? The geological evidence which distinguishes our eras from one another may continue to defy the ravages of time. The earth writes its history as it ages, and possibly enough will be there for that future geologist if he can decipher nature's hieroglyphics.

To complete the catalogue, we list the periods and some of the epochs into which the eras are divided. One does not need to be a student of geology to hear references to the Pleistocene, the Miocene, the Pennsylvanian, the Silurian and other similar terms. The names are in the table, not to be memorized, but for ready reference.

To plunge at once into an account of diastrophism, volcanism and glaciation would leave this rapid summation to stand as a bald catalogue of eras and epochs. What are some of the changes that time has wrought in the earth's outer shell? Heretofore we have consistently gone backward in time in naming eras and epochs; now we reverse the order, and start as near the beginning as we can. The preceding chapter prepared us to expect a continuing process of wear and tear, and there was also brief mention of *isostatic* adjustments—those cyclic risings and sinkings of the crust which apparently tend to equalize the differences of pressure produced by two pairs of processes: erosion and sedimentation, and the forming and melting of continental ice sheets.

Except by astronomical evidence we cannot trace the earth back to the time when, in all probability, planetesimals torn from the sun by the tidal effect of a passing star were falling into one of the larger of their number to form our planet. The earliest *Archeozoic* records reveal an earth already formed. Traces of sedimentation suggest that in a still earlier age the processes of erosion and deposi-

tion had been at work, and some rock of both sedimentary and igneous (molten) origin had already been metamorphosed into other types. Volcanism, at least of the underground sort, made its mark. Molten rock was forcing its way into crevices and weak regions of other rock. Solidifying there, it left crystalline proof of a difference of age. *Igneous intrusions,* as the results of this action are called, are one of the geologist's chronometers: the new rock is obviously younger than that into which it intrudes. The records of this early era are not well preserved; but there are some indications that extensive mountain ranges were thrust up and then eroded in Archeozoic times. One seeking a quick characterization of the Archeozoic era might look on it as the earliest age of life. No fossils dating back to this era have been found, but the existence of life of the simple one-celled sort has been inferred from the general trend of organic evolution in succeeding eras. For example, throughout the era which followed the Archeozoic, seaweeds grew, and certain chemical actions which are commonly promoted by the vegetable micro-organisms called bacteria seem to have occurred. It seems unlikely that these forms of life did not have simpler ancestors in the Archeozoic. But every geologist will confess to a great deal of uncertainty here.

In the *Proterozoic era,* the records become somewhat clearer. Nickel, silver, gold, copper and, notably, iron ores, were laid down in abundance. Igneous processes, the result of heat, were responsible for concentrating the first four of these metals; but there is no need to regard the earth as having been largely molten. The iron ores seem to have been deposited by sedimentary action. We noted above that evidences of sedimentation have been detected as far back as the Archeozoic. Sedimentary action presupposes the existence of seas and rainfall — conditions which are obviously incompatible with a hot exterior. Opinion today leans to the idea that

the earth started its planetary career as a solid. The *planetesimals* which supposedly fell together to form the earth must have passed through the molten condition after having been torn from the hot, gaseous sun; but probably all but the largest planetesimals cooled and solidified very quickly. The deposits of metals are one of the outstanding characteristics of the Proterozoic era. Many of the richest mines in the United States and Canada owe a debt to this early era. Another characteristic is the continuing development of life. Even in the earliest epochs of the Proterozoic, seaweeds and bacteria were present, and probably sponges as well; and before the era ended a great variety of invertebrate forms of animal life seem to have made their appearance. But identifiable remains are rare; uncertainty exists. Approximately where the Appalachian and the Rocky Mountains now stand, there were two great troughs, elongated depressions called *geosynclines,* and these were gradually filling up with sediments.

The Archeozoic and Proterozoic together account for nearly three-fourths of the two billion years which we are considering so rapidly. Coming to the *Paleozoic,* we are within striking distance, geologically speaking, of present times. The Cambrian epoch, the oldest of this era, is commonly used as a landmark in geology. Formerly, everything older than this was dismissed rather abruptly as pre-Cambrian. If our hypothetical one-hour film of geological history were to start at 8:00 P.M. and bring us to the present moment promptly at nine, pre-Cambrian times would end, and the Paleozoic era would begin its showing, at about sixteen minutes before nine. Only sixteen minutes left, but what a sixteen! Vegetation thrives; invertebrate life abounds. Through most of this era the seas reign. Early in the Paleozoic era, large portions of continents were flooded by the sea, and were repeatedly submerged during the first four periods of the six that form this era. In the next to the earliest Paleozoic period (the Ordovician), three-fifths

of North America was under water. The Indiana-wide sea which we conjured up to illustrate the volume of a few months' rainfall in the present Mississippi valley would represent only a small fraction of the wet reality in early and mid-Paleozoic time. Dreadnaughts could have traversed what is now the widest part of the United States.

With so much water, the climate was mild. Among the Paleozoic invertebrates may be mentioned trilobites, corals, jelly-fish, sponges, amoeba, worms, starfish, clams, oysters, snails, squids, spiders and centipedes. Trilobites dominated the seas at the beginning of the era and became extinct at its end; their fossils help to identify Paleozoic rocks. Primitive vertebrates, including armored fish and sharks, appeared. The Appalachian trough, and the one approximately where the Rocky Mountains now stand (the *Cordilleran* geosyncline) continued to fill with sediment, increasing the pressure on the supporting rock. Ferns, mosses, and pines flourished. The earliest great forests grew in the Devonian period, and subsequent vegetation provided the raw material from which the Pennsylvanian coal fields were formed when submergence of forest-covered land brought about the necessary conditions. Most of the world's coal dates back to this era. Oil, also, was formed, probably by the action of bacteria which fed on the organic matter in the sediments.

Diastrophic movements of subsidence and uplift increased towards the close of the Paleozoic. The great extent of the seas and the abundance of marine life induced heavy sedimentation, and this, in turn, caused inequalities of pressure. Continents rose again from the sea. Mountain-building occurred on a world-wide scale. The Appalachian trough folded; the Appalachian Mountains were born. And the climate changed. We find this exciting era ending on a cold note: glaciation!

Now, by our 8:00 to 9:00 P.M. scale of condensed earth history,

it is six minutes before nine. We enter the last but one of the great geological eras — the *Mesozoic*. Primitive mammals appear at the beginning of the era — but the mammals must wait until the most recent era, the Cenozoic, before they succeed to the throne. The Mesozoic is the age of reptilian dominance. Primitive reptiles had made their appearance shortly before the close of the Paleozoic, but now they develop those monstrous forms which distinguish the Mesozoic. Not all dinosaurs were enormous, indeed some were no larger than a modern man; but in Tyrannosaurus they produced a carnivorous representative measuring up to fifty feet in length. Heads armed with teeth half a foot long towered twenty feet in the air. It was an age of bloody battle in the animal world, and Tyrannosaurus, the king, by the measure of brute force, of all the creatures that have inhabited the globe, reigned supreme. Certain herbivorous dinosaurs (Diplodocus, Brontosaurus, Brachiosaurus) grew to be nearly twice the length of Tyrannosaurus, but, despite their superior size, probably fell easy prey to their predatory relatives. The daily refueling of a 30- to 50-ton Brachiosaurus must have presented a physical problem of no mean magnitude. For about three minutes of our 60-minute showing time, or 100,000,000 years of actual duration, the dinosaurs dominated the animal world. Remains of these monsters are found distributed on a world-wide scale. America, especially western United States, seems to have somewhat more than its fair share of well-preserved specimens. Flying reptiles, too, appeared, and birds. Then ill fate overtook Mesozoic life: there was a wholesale extinction of characteristic species in the closing epoch.

Meanwhile, the earth's crust was adjusting itself. Continents uplifted at the close of the preceding era continued emergent during the first half of the Mesozoic, but sagged again in the Cretaceous period. The subsidence brought continental seas in its train.

Heavy sedimentation weighted the one great remaining trough in North America, the Cordilleran geosyncline. Eventually — doubtless for the same reason that the Appalachian geosyncline had folded at the close of the preceding era, forming the Appalachian Mountains — the Cordilleran geosyncline folded at the close of the Mesozoic, and the Rocky Mountains were born. Touring these two great mountain regions of the United States, one can tell by the greater height and ruggedness of the Rockies that they are younger than the Appalachians. But continuing gradual uplift has been needed to maintain the heights of both these ranges against the destructive processes of gradation. Uplifts such as the folding of the Cordilleran geosyncline, and subsequent carving of valleys, expose ancient rock for examination. Igneous rock of the early Archeozoic era lies at the bottom of the walls of the Grand Canyon.

We reach the last minute and a half of our one-hour condensation of earth history. The beginning of the *Cenozoic* era finds the principal continental features of North America well established. The Rocky Mountains and the Appalachian range have already been formed. The day of widespread continental seas has passed. Some marginal sinking of land near the southern and western coast lines of North America occurs early in the era, in the Tertiary period. The Florida peninsula is under water during part of the Tertiary, and areas now included in the states of Alabama, Mississippi, Louisiana, Texas, Washington, Oregon and California are partially submerged, but there are no signs of widespread continental inundation. Mexico shares in this coastal submergence. The Tertiary sediments deposited during the inundation attain an exceptionally great depth on the submerged parts of Texas and Louisiana. There the maximum thickness is several miles. The great weight of these sediments is believed to have been

an important factor in the crustal readjustments which produced the Texas and Louisiana oil-bearing salt domes. These rounded plugs of salt are intruded up into the Tertiary sediments from older rock below, and the convex curvatures which they produce in rock strata form a favorite site for the collecting of oil into pools.

The Tertiary period of the Cenozoic is marked by volcanic activity. Several well-known mountains of the Cascade range, including Mt. Ranier in Washington and Mt. Shasta in California, owe their origin (and their picturesque symmetry) to volcanic activity of the Tertiary period. Large areas of Idaho, Washington and Oregon were covered with lava. Successive flows of this molten rock built up thicknesses ranging, in different places, from 80 or 100 feet to approximately a mile. Amethyst Mountain, in Yellowstone National Park, contains remnants of more than a dozen forests buried in tiers by successive lava flows, one on top of the next. The flows must have continued at intervals for a long time; for there was time for the upper crust of one hardened lava bed to weather into soil before the next flow arrived to destroy the forest that had sprung up. Other evidences of underground commotion during the Tertiary are well known. Upheaval occurred: the Alps, the Carpathians, and the Himalayan mountain range were formed. High up in the Himalayas, several miles above the present level of the sea, ocean sediments of the Tertiary period have been found.

The uplift of land was accompanied by a change of climate from mild to cold; and on entering the Pleistocene epoch of this era we encounter the four successive glaciations which were mentioned a few pages earlier. The tracks of these great continental ice sheets have been thoroughly traced. The telltale signs are many. The slowly moving mass carries rocks held in an icy grip, and with these natural tools it engraves a characteristic record in the bed

rock over which it moves. Masses of debris are dropped in long ridges called *moraines*. On retreating, the ice sheet may leave clay arranged in seasonal bandings to mark its yearly recession. The glaciations covered large parts of both hemispheres. In North America they are called (in token of their farthest southern advancement) the Nebraskan, the Kansan, the Illinoian, and the Wisconsin. The names are listed in order of age, earliest first. Drainage was profoundly influenced by these glaciations. Only since the retreat of the last Pleistocene ice sheet have the present arrangement and drainage system of the Great Lakes existed. Lake Michigan and Lake Erie, and Lake Winnepeg as well, once drained into the Mississippi.

Other changes occurred. The sequestering of so many billions of tons of water to form the continental ice sheets lowered the sea level. The temporary subsidence of the water extended coast lines outward. Channels of erosion could now form in land that had hitherto been under water; and outlying portions of ocean floor that had previously been too far from the coast to receive the heaviest deposits, now underwent extensive sedimentation. Subsequent melting of continental ice sheets raised the level of the sea by an amount conservatively estimated at several hundred feet. The amount cannot be stated exactly; but measurements show that even now, the release of the water stored in the Antarctic and Greenland remnants of the Pleistocene ice sheets would raise sea level nearly a hundred feet. The Pleistocene melting, and rise of sea level, drowned the mouths of valleys to form estuaries, and left far off-shore portions of the ocean floor which had previously been built up by coastal sedimentation. An interesting inland example of the drowning of valleys to form wide mouths can be seen along the south shore of Lake Superior. The north shore is high and rugged, but the south shore contains a number of harbors of the

wide, drowned-valley type. Evidently the land of Canada rose when relieved of its weight of ice, and the tilting dumped Lake Superior against the opposite shore. This uplifting of Canada still continues at a rate which, if maintained, would in less than

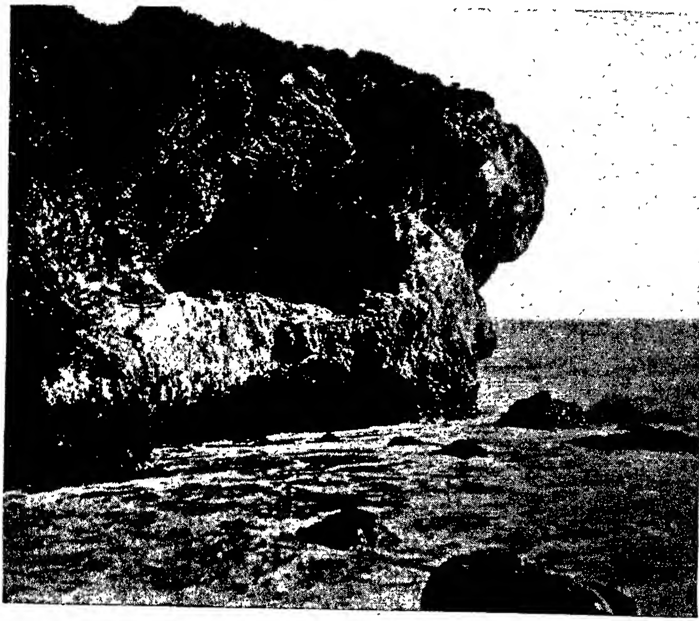


FIGURE 71. What force elevated this wave-cut cave to its present height above the sea? (Photographed near Port San Luis, California, by G. W. Stose, U. S. Geological Survey.)

two thousand years cause the upper Great Lakes to drain into the Mississippi through the Chicago River.

Throughout the Cenozoic era, mammals were advancing. Mastodons date from the Oligocene epoch of this era, but apparently did not make their way to North America until the Miocene. Numerous remains attest their presence here from then on into

the Pleistocene ice age. Apes appeared in the eastern hemisphere in the Miocene epoch. In Pliocene strata, there are crudely fashioned flint implements which must have been shaped by man-like creatures. Workmanship improved during the Pleistocene epoch and the bones of the Piltdown man, the Heidelberg man, and Neanderthal man are associated with the glacial and interglacial deposits. Finally, as the last of the great ice sheets began to melt away, modern man as represented by the Cro-Magnon race appears. So far as the discoveries to date reveal, the earliest records of the existing human species are only about 30,000 years old. How young the precious relics of man's infancy seem to the geologist! Thirty thousand years against two billion! Let the historian of human affairs pick up the thread, while we consider some causes of the great prehistoric changes in the appearance of the earth.

Earth Convulsions — And Slow Adjustments

In dealing with possible causes of the actions which have altered the earth on so grand a scale, we must proceed with caution. A few suggestions of interplay of cause and effect have been included in our summary of earth history, but even a rapid reader will have noticed that *approximately, seems, probably,* and other indications of lack of certainty have appeared. To claim too high a degree of accuracy or of certainty in a field in which the evidence carries one back into almost unimaginably remote vistas of time is as far removed from the spirit of science as it would be to reject conclusions when the evidence to support them stares one in the face. It is barely a century since William Smith, the founder of the English historical geology, died. The progress of the science during that short period is one of the great achievements of the race. The bold

outlines of earth history are not likely to be changed by the results of further research. Details, however, must still be inked in; many probabilities remain to be either confirmed or superseded — and as for the underlying causes of the three great processes of earth-moulding (gradation, to which the preceding chapter was largely devoted; volcanism, and diastrophism), only gradation can be said to be thoroughly understood. Clear thinking demands that we distinguish sharply between the two questions, "Why did such-and-such an event occur?" and "How do we know that it occurred?" For example, the geologist can pile up mountains of evidence to prove that the earth's crust has heaved and sagged many times and in many places — but precisely why a given upheaval or subsidence occurred, and why it occurred when it did, remain, at least in part, matters of conjecture.

We read of earthquakes in the newspapers, and know for certain that diastrophism exists. The solid crust does shift. In the San Francisco earthquake of 1906, roads crossing the San Andreas fault were broken and displaced. They looked as if the road-builders had worked from both ends and failed to meet! One straight road was displaced twenty-one feet to the side — so far that two dead ends were formed. What force broke the crust and pushed the road aside? For nearly three hundred miles along the San Andreas fault the crust at one side of the fracture slid past the neighboring rock. Like an automaton bowing a mighty violin, the momentary river of solid rock grated against its confining wall; the vibrations caused great damage. In 1899, an Alaskan earthquake lifted part of the coast vertically upward nearly fifty feet, and made new waterfalls. Slower adjustments are observed. Comparing the results of precise measurements made in 1926 and repeated in 1935, we find that the distance between North America and Europe is decreasing very slowly, and that even within the con-

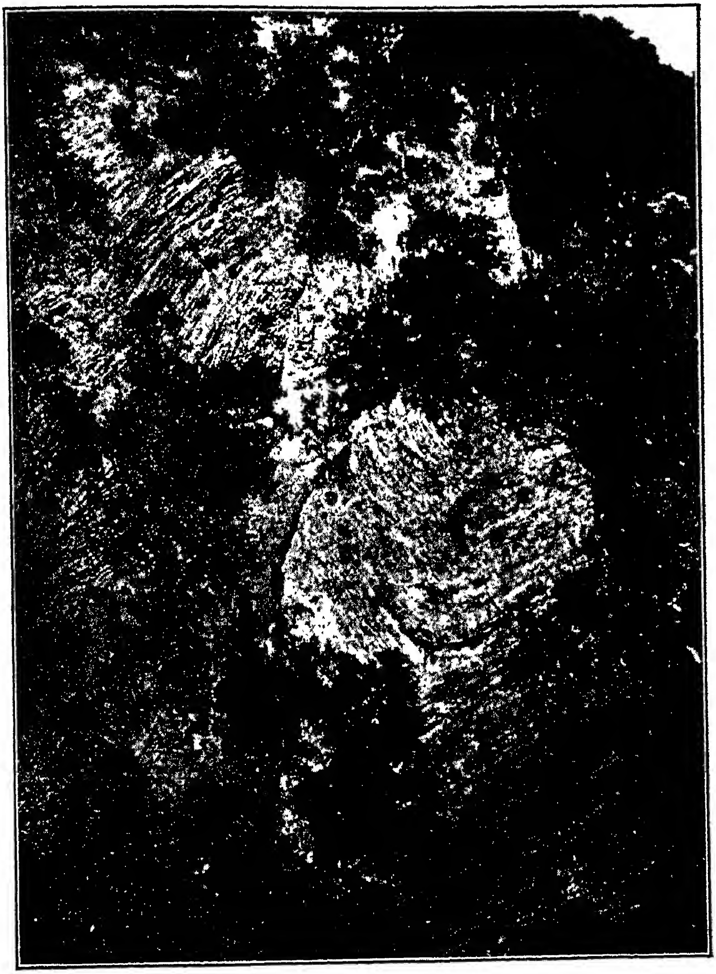


FIGURE 72. Rock folds. (Courtesy U. S. Forest Service.)

tinent movements occur. San Diego is receding from Washington, D. C., at the rate of about 440 feet per century.

But recent movements are only a small part of the evidence of diastrophism. High above sea level, just under the overhanging

FIGURE 73. The steep inclination of these once-horizontal strata of rock gives evidence of the diastrophic forces which alter the earth's crust. (Photographed by William J. Miller.)

crag of a towering cliff, one sees here and there a cave which shows unmistakable signs of having been hollowed out by ocean waves. What forces hoisted the wave-cut cavern? In every great mountain range, marine fossils and other evidences of sedimentation are found. How did it come about that the ocean floor was lifted? In those same mountain ranges, where bare walls of rock are exposed to view, the conspicuous strata of sedimentary rock — rock that was laid down in horizontal strata on the bottom of the sea — are now bent and folded in many places. Some of these once-

horizontal layers are steeply inclined, some stand on end; and here and there one can trace a many-layered thickness along a course that curves regularly up and down, making a series of sinuous waves along the mountainside.

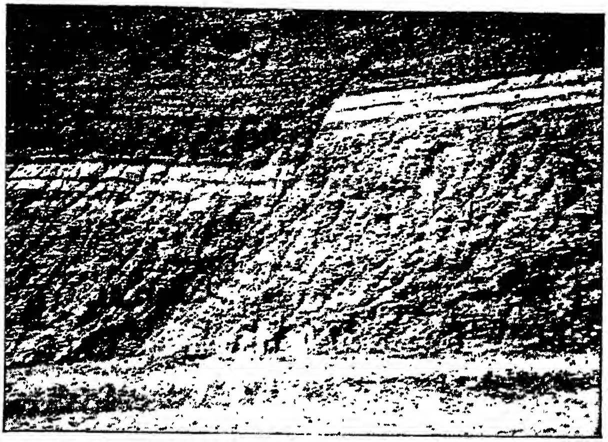


FIGURE 74. A fault in the rock: evidence of diastrophism. (From *Introduction to Physical Geology,* by William J. Miller.)

Stretch a sheet of corrugated paper out flat, then push in from the two sides and watch it crumple into folds. How great must the forces have been which folded solid rock in thicknesses ranging from hundreds to thousands of feet! Now, with the sheet of corrugated paper lying on the table, imagine the tops of all the crests of the folds to be shaved off cleanly. Looking at the edge of the paper, one could still trace the folds: the imagination would fill in the gaps. Just so, the geologist, after getting used to the folding in a given region, can reconstruct the region as it was before erosion removed the tops of the crests. He sees outcrops — layers of rock intersecting the surface at angles as he marches along a flat plateau. The next place where he will find the roots of a returning fold

striking down into the ground at the expected angle, or coming up to intersect the surface, may be in the next county, but find them he does — and by this means has often discovered a new or better access to a given vein of rich ore.

Or, instead of *folds,* he may find *faults.* A long horizontal tier of stratified rock may come to an abrupt end; but glancing up, or maybe down, he finds the same tier of layers continuing on across the mountainside. Picturing those straight roads that were broken in two and displaced laterally to form dead ends where they crossed the San Andreas fault, he knows the answer to this puzzle. Measurements show that the two ends would make a perfect match, thin layers matching thin, and thick, thick. A microscopic analysis of the texture confirms the result. The two tiers were once continuous, but a tremendous force broke the layers and either elevated one part or lowered the other.

Faults, folds, drowned valleys, and fossils in the mountains supplement the evidence of earthquakes. Why has the earth's solid crust of rock been repeatedly crumpled, fractured, lifted and depressed? If no continuing processes were at work to disturb the equilibrium, two billion years would seem long enough to permit an aggregation of solid planetesimals to settle and stop shifting. And even if the earth began as a molten body, it doubtless solidified relatively early, as geological time goes. We learned in the preceding chapter how we know that the earth, except for local pockets of molten rock, is solid now, and there is no reason for believing that the solidification has occurred recently. Sedimentary rock deposited in a *liquid* ocean is characteristic of all the eras that we know, and signs of seaweed extend back to the Proterozoic. Through all those two billion years that we have mentioned so often, the earth seems to have had a solid crust, and oceans and air. What we have to consider is not an earth that is still struggling to

recover from the shock of having been born, but an earth whose faulting, folding and other diastrophic adjustments are normal and may be expected to continue as long as the earth lasts.

Many have found it difficult to accept this result of twentieth-century studies. The molten globe theory, a natural consequence of the unsound nebular hypothesis, explained so many enigmas, and so easily! The surface would cool first, of course, and a crust would form. Further cooling, and solidification of additional lava under the outer crust, would cause contraction. The outer crust, already solid, would be obliged to crack and wrinkle as the hot core that supported it shrank inward towards the center. Mountains and chasms would form, and sea basins. There is abundant evidence to suggest that the earth *has* contracted. Straightening out the folds now found in mountain ranges would make the crust much too large to fit the earth. In the northern Rocky Mountains, one of the lateral (thrust) faults once pushed a mass of rock nearly two miles thick about eighteen miles eastward. So long as the molten globe hypothesis held the field, the clearest and simplest explanation of folds and thrust faults was found in the contraction which a cooling and solidifying earth would necessarily undergo. We saw in Chapter 4 how confidently (and with how great an error!) Lord Kelvin calculated the age of the earth on the basis of its supposed cooling. The discovery of radioactivity — a process which continually produces heat in the earth's interior — removed the foundation on which Lord Kelvin based his calculations, and the same action of exploding atoms makes it unnecessary to regard the many signs of high temperatures and flow of heat in the earth's outer shell as sure evidence of continuous cooling from a still hotter condition in the past.

Our knowledge of the amount and distribution of radioactive matter in the earth is incomplete. Further, any contraction or set-

tling of the earth, whether due to cooling or to other actions, changes the potential energy of high position into heat. Enough heat may be produced by radioactivity, or by radioactivity and contraction combined, to account for all the evidences of heat. This possibility, together with the dynamical evidence that the momentum of the planets was imparted to them by a body now outside the solar system, has greatly weakened the molten globe hypothesis. The easy explanation of mountain-building by cooling and contraction is not as satisfying as it once seemed to be.

But contraction may have resulted from causes other than cooling. Slow recrystallization of matter under the tremendous pressures in the earth's interior may have caused shrinking. Or the same great pressures (6580 billion billion tons of matter press inward on the center) may have compressed the atoms themselves. The facts reviewed in Chapter 10 showed how large the empty spaces in atoms are in comparison with the space actually filled by what we call material substance. A diminution of the empty spaces which separate atomic nuclei from their outlying electrons is conceivable, and in the aggregate might account for all the contraction which mountain-building and other folding and faulting of the earth's crust seem to show.

Finally, there are the ideas of isostasy, which we have mentioned so often. If the earth's crust periodically readjusts itself so as to maintain an approximately constant pressure at a depth of a few tens of miles beneath the surface, the changes which the outer crust has undergone can be understood. We know that erosion and sedimentation continually redistribute matter, and the pendulum measurements mentioned in our study of the earth's interior show that, cubic mile for cubic mile, the materials under the oceans weigh more than do those in mountainous regions. Periodic readjustments to counterbalance the lightening of continents by ero-

sion and the weighting of sea bottoms by sedimentation seem to be at least one factor in the building of mountains and continents, and may be the principal factor. Provided we do not interpret contraction as implying the continuous cooling of a once-molten globe, the safest position to adopt is that both contraction and isostatic adjustments have been at work.

Volcanic Activity

But whether the heat of the earth's interior is largely residual, left over from a hot beginning, or whether it is maintained by continuing actions, there can be no doubt that high temperatures have played an important role in fashioning the earth. The Vesuvian fate which descended on Herculaneum and Pompeii in A.D. 79 was merely one sign of an agency that is world-wide in its scope. More than four hundred active volcanoes are known today, and several thousand additional volcanoes are either recently extinct or in the dormant, or quiescent, state which punctuates the history of these violent agencies of terrestrial evolution. Hot springs and geysers abound. The wide distribution of granite and other igneous rocks shows that stony material by the billions of tons has at one time or another flowed as a liquid. Volcanism has been at work in all the five great eras that we know. Some igneous rock dates back to the Archeozoic; some is being formed today. In western India a third of a million square miles lies buried under sheets of lava. Successive flows have built up a great lava plateau there; in some places the total thickness is more than a mile. In one section of Great Britain erosion is gradually disclosing lava beds of great antiquity. Volcanic action under the sea threw up the Aleutian Islands, forming a chain of gigantic stepping stones from Alaska to Siberia. Three new tiny islands of this chain were

formed by eruptions in 1796, 1883, and 1906. Many of the Indies, both East and West, are islands of volcanic origin; likewise the Hawaiian Islands. Five mighty volcanoes—including Mauna Loa, the largest of all present volcanoes — rear themselves to majestic heights above the lava-built island of Hawaii.

The lava plateau in our own extreme Northwest began to be formed in the most recent era, the Cenozoic. Today these lava beds in Idaho, Oregon, Washington and a portion of California cover nearly a quarter of a million square miles. At Gular, Washington, one can walk around in a lava tunnel forty feet high which was formed by the draining away of still-molten lava from beneath its solidified crust. Obsidian Cliff in Yellowstone Park presents to the tourist a beautiful exhibit of volcanic glass — lava which solidified so quickly that the molten rock did not crystallize. The Cascade range in this section of the country is partially volcanic in origin: its most impressive peaks—Adams, Baker, Ranier, Hood, Shasta, Lassen — are volcanic cones. The last of these, Lassen Peak in California, gave the geologists of the United States their first opportunity to observe an eruption in their own country. This decadent volcano, after having remained inactive for an undetermined number of centuries, resumed action shortly before the outbreak of the World War, and the following year (1915) produced two explosive outbursts of steam, mud, and hot (but not molten) rock, which laid a beautiful countryside waste for ten miles or more. Farther north, in Alaska, Mount Katmai nearly destroyed itself by an explosion in 1912. The whole top of the mountain, several cubic miles of rock, was blown away in an appalling display of the forces produced by high temperatures underground, and the Valley of Ten Thousand Smokes was born.

The chapters in which we discussed man's success in applying science to modify his environment now seem remote, indeed. Cap-

ping a burning oil well presents difficulties. What sort of confining armor, what straitjacket, would one fit to the earth to subdue forces that can topple old mountains, build new ones, or rear islands from the ocean floor? What actions bring forces of so great a magnitude into being? Dotting a map of the western hemisphere to show the locations of active or recently extinct volcanoes, one finds the dots making a great chain that extends from Cape Horn to Alaska along the Andes and the Rockies. Where the Cordilleran geosyncline folded to form these mountain ranges is precisely where volcanic activity is concentrated! The same relationship exists the world over. Those belts of the earth where diastrophic movements of the crust have occurred and are now likely to occur, are the places where volcanic action is prevalent. This significant relationship poses several questions. Do the diastrophic movements, the folding and faulting of the rocks, *produce the heat* which volcanic activity releases? Do they *permit melting* to occur at the expense of heat that the rock possessed beforehand? Or do the fractures resulting from the diastrophic movements merely *provide paths* along which rock already molten can escape with relative ease?

This last hypothesis might seem to offer a complete explanation if there were a universal sea of liquid rock beneath the outer crust, and if only fissure volcanoes were known, the kind whose lava wells up without violence from long cracks or fissures in the rock. But many examples can be cited to show that eruptions do not always follow the paths which, at least to judge by surface topography, would seem to be the most likely. At the Grand Canyon of the Colorado, volcanoes have ignored the apparently easier access to the surface through the bottom of the mile-deep cut, and forced openings to the top of the towering wall. What this really means is that the action is too deep-seated in the crust to be greatly

influenced by the surface topography. And as for the universal sea of molten rock, we have cited abundant evidence to prove the earth's solidity. To clinch the point, the outlets of Mauna Loa and Kilauea, two of the great volcanoes of the island of Hawaii,

FIGURE 75. A lava-flow over the edge of an old lava tunnel at Kilauea, Hawaii. (William J. Miller.)

lie only twenty miles apart, yet each discharges independently of the other! If both these volcanoes were fed by a common pool, as many of our oil wells are, their periods of eruption would coincide. One is forced to conclude that volcanic action is *localized* not only at the surface, but underground as well.

But if the providing of paths by diastrophic fracturing cannot furnish a complete explanation, it is at least a means whereby pressure on the underlying rock can be relieved. The production of heat by diastrophic movements, though doubtless great, can hardly

account for the formation and *maintenance* of the localized pockets of molten rock which feed volcanoes. The second of the three possibilities mentioned above is more promising. Relief of pressure may permit rock to melt.

Here we encounter a principle of physics. Reducing the pressure facilitates a change of state if that change of state is one which involves expansion; *and vice versa.* Since pressure opposes expansion, one might expect that a change which makes it easier for a material to expand will further an action that requires expansion, and this turns out to be true. If a substance expands when melting, *decrease* of pressure enables the material to melt at a lower temperature than would otherwise be required. But if the substance contracts when melting, as ice does, *increasing* the pressure lowers the melting point and promotes melting. This accounts for the self-lubricating action of glaciers and ice skates. Similarly, in the case of boiling. Vaporization involves an increase of volume; lowering the pressure facilitates boiling. Deep in the neck of Old Faithful Geyser, the pressure of the long column of water is so great that the adjacent hot rock must heat the water far above the normal boiling point if boiling is to occur. When the water does begin to boil at the bottom, some water is forced out at the top, the pressure is relieved, and the now superheated water boils up with explosive violence. Inflow of ground water fills the neck again, and 65 minutes later Old Faithful erupts again. Rock samplings obtained recently by drilling to a depth of 406 feet showed that the action of Old Faithful began at least early enough to be temporarily interrupted by the last glaciation. Thus *geysers* — a minor manifestation of volcanism — are understood; but the point we are especially interested in here is that relief of pressure can produce an analogous action in heated rock. Unlike ice, rock expands when melting; hence reduction of pressure by diastrophic

FIGURE 76. Evidence of volcanism about forty miles southeast of Grand Canyon, Arizona. The dark lava-flow extends from the base of a cinder cone. (Fairchild Aerial Surveys.)

adjustments will induce melting provided the solid rock is already sufficiently hot.

Thus we formulate a probable sequence of actions. The earth's interior is hot but solid. Radioactivity is one action that helps to keep the underlying rock hot. Contraction — certainly a very slow contraction, if any — may be another. Diastrophic movements of the earth's crust occur at intervals. Isostatic adjustments, and possibly contraction, may account for these. The movements relieve the pressure in parts of the affected regions, permitting some rock to melt in localized pockets. The same crustal movements produce faulting, opening avenues along which molten rock may rise nearer to the surface. But what causes the explosive violence? Steam and other gases are commonly associated with volcanic outbursts, in enormous quantities. Where the water enters the picture is not clear. It is possible, though not likely, that ground water may seep down far enough to mingle with the molten rock and produce a geyser-like action on a grand scale. The alternative is to suppose that water has been trapped in deep rock since the earth was formed. If that is the case, volcanic action is gradually drying out the interior of the crust.

To present a more definite explanation of volcanic action would do violence to the present state of knowledge. The problem has not been completely solved. Concluding our brief résumé of the uncontrolled agencies which help to fashion our physical environment, we turn to one possible effect of volcanism — its effect on climate. Were those cold periods of the Pleistocene glaciations the result of volcanic activity? The evidence is slender, but let us see where this apparently self-contradictory question leads.

Causes of the Ice Ages

In 1784 Benjamin Franklin suggested that the exceptional severity of the winter of 1783–1784, and the coolness of the preceding summer, might be attributed to obstruction of the sun's radiation

FIGURE 77. Crevasse in South Sister Glacier, Oregon. (U. S. Forest Service.)

by a dry "fog" which pervaded the upper atmosphere of Europe and North America. The cause of the widespread "fog" he did not know; but among other conjectures he remarked that it might have been formed by vast quantities of smoke issuing from two volcanoes, one in Iceland proper, the other a volcano that rose from

the sea offshore. The three cubic miles of lava which welled up gently from a twenty-mile-long fissure at Laki, Iceland, in 1783 was one of the most voluminous single discharges of molten rock recorded in dated history. Eruptions of the explosive type, the kind that is most effective in distributing volcanic dust through the atmosphere, also occurred in the island. The same year witnessed an eruption in Japan which far surpassed the Icelandic outbursts: Mount Asamayama exploded. The records show that 1784, 1785 and 1786 were indeed cold years. In the midst of this period, Vesuvius contributed more than its usual quota of volcanic dust to the atmosphere. Suppose the idea underlying Franklin's suggestion be true. If recurring periods of coldness, including rigors as extreme as the Pleistocene ice ages, can be traced to the hot craters of the world, one may fancy for a moment that poetic justice is a principle of geology.

The *volcanic dust hypothesis* (to which we shall return farther on) is one of many interesting and varied attempts to account for climatic changes. Every proposed explanation has encountered criticism. In surveying the earth's history we found that the climate had often changed from warm to cold, and back again. Tropic vegetation once grew in Greenland. The arid wastes of deserts have reposed on sites now occupied by Germany, Ohio, New York. An aging man renounces forever certain feats that he tossed off lightly in his youth; an aging earth need not. A molten globe continuously cooling could not repeat all the passages in its history, but that view of the earth has proved unsound. In the realm of climate, what has happened once, can happen again. A repetition of the Pleistocene glaciations, which *were* repeated several times during one short epoch of the most recent era, would overshadow all the catastrophes of man's history. And the Pleistocene ice ages were merely an incident in the history of climate.

Debris left by still earlier ice sheets has been found in the torrid zone. If actions of a roughly cyclic nature have been, and are, at work, an understanding of the past should enable us to predict the general outlines of the future. Despite many uncertainties, the picture is gradually becoming clearer. No longer need one grope for *any* action that might have been responsible. Instead, the doubt now centers on the relative importance and probability of actions known to be possible.

The probable importance of *astronomical* factors of climatic control has been vigorously debated. The earth receives its surface heat from the sun; it revolves about the sun in an orbit that is not quite circular; and it shares in the motion which carries the sun and its whole family of planets towards the constellation Hercules at a speed of about twelve miles a second. Furthermore, the earth's axis wobbles slowly, producing an effect called the precession of the equinoxes, and this regularly reverses seasonal conditions in so far as their relative severity in the northern and southern hemispheres is concerned. We noted in Chapter 15 that at present both winter and summer are moderated in the northern hemisphere, and intensified in the southern, because the earth is a few percent nearer to the sun in January than in July; but every twelve thousand years the situation is reversed, and the other hemisphere is favored.

These and other astronomical factors might seem to present a wealth of possibilities. The amount by which the earth's orbit departs from a circle (its eccentricity) varies slightly as the years roll by, passing through a cycle which averages a thousand centuries in length. This must cause slight changes in the contrast between seasons in the two hemispheres. The whole solar system may conceivably have encountered dark nebulous matter in its journey through the galaxy — invisible cosmic clouds which would

temporarily reduce the earth's income of energy from the sun. And of course the sun itself is a variable star. The fraction of its surface that is darkened by spots increases and decreases in cycles about eleven years long, and may possibly have varied between wider limits in the past, and at longer intervals. Despite the sun's superficial commotion, however, it seems as a whole to be a very stable body, and almost unimaginably long-lived. The newer physics indicates that it is radiating its material substance away as energy, but the rate of transformation is estimated to be so slow that it loses only one to two ten-thousandths of itself during a period as long as all five of the geological eras that we recognize. To attempt an appraisal of the possible astronomical factors of climatic control on their individual merits would carry us far beyond the bounds of this chapter. We merely cite one fact which apparently relegates them all to unimportant roles. *All the known ice ages have occurred at times of mountain-building and continental uplift, or very soon thereafter.* Is it likely that the same *astronomical* agencies have caused *both* mountain-building and ice ages?

Clearly, the earth manufactures its own ice ages. This conclusion narrows the field, but still leaves many possibilities. Uplift of land changes the circulation of air. Remember the dry Chinook wind which promotes aridity on the eastern slope of the Rocky Mountains. Ocean currents are affected. A relatively slight diastrophic adjustment could drown the Isthmus of Panama and destroy the Gulf Stream; a subsequent uplift would again deflect the westward-bound equatorial current northeastward and recreate the Stream. A major increase of the ratio of land area to sea would deprive much land of the stabilizing influence of contiguous water and thus substitute the rigors of continental climate for island mildness. Oceans would shrink as continents rose,

hence the amount of water vapor in the atmosphere, averaged over the earth's surface, would decrease. By the *greenhouse effect,* water vapor in the air promotes higher surface temperatures: it is more transparent to the incoming radiation from the sun than to the longer waves of outward bound heat radiation emitted by the earth, hence helps to trap the heat. Reduction of the amount of water vapor would diminish this warming influence.

Carbon dioxide, too, contributes a greenhouse effect. Its density in the atmosphere would be expected to diminish when the exposed land area increased, for two reasons. Uplift of land helps to remove carbon dioxide from the air by increasing the chemical weathering of rock; and at least one source of supply of carbon dioxide — the chemical action involved in the precipitation of limestone in the sea — is reduced by the shrinkage of oceans that attends the elevation and enlargement of continents. Other factors, notably changes in the luxuriance of vegetation, which consumes carbon dioxide, need critical evaluation. The *carbon dioxide hypothesis* of climatic control cannot be dismissed, but recent studies suggest that its importance may have been overrated.

Laboratory measurements show that the greenhouse effect is not very sensitive to changes in the amount of carbon dioxide in the air. Dr. W. J. Humphreys, dealing with climatic controls in Part V of his authoritative treatise, "Physics of the Air," concludes that doubling or even tripling the amount of carbon dioxide in the atmosphere would not raise the average surface temperature of the earth by more than 1.3 degrees centigrade, and that a correspondingly large decrease, say to one-half the present amount, would not lower the average temperature by more than that same small amount. Of course, if all three of the gases (carbon dioxide, water vapor and ozone) which produce the greenhouse effect by their selective absorption of the earth's outward-bound heat radia-

tion had ever disappeared from the atmosphere simultaneously, there would have been a larger drop of temperature. But the ozone could not have disappeared unless the ultraviolet of sunlight, which forms it, had ceased to reach the upper atmosphere — a wholly improbable supposition; and the evidence that open water and vegetation existed in non-glaciated regions during the ice ages shows that the amounts of water vapor and carbon dioxide could not have been negligible. Apparently, another agency must be sought if the extreme rigors of the ice ages are to be explained.

That other agency may already have been discovered. We come now to an action which, twelve times in the last two centuries, seems beyond reasonable doubt to have been the principal cause of unusual, world-wide coldness lasting one to three years at a time. The coincidence of persisting cold weather and violent volcanic outbursts during that period is a matter of record. The conditions which called forth Benjamin Franklin's shrewd observation have been repeated many times. To mention only the most frightful eruptions of the period, Mount Asamayama exploded in 1783, Tomboro in 1815, Krakatoa in 1883, Pelée in 1902, Katmai in 1912. Every one of these major outbursts was followed by two or more years of exceptional coldness. Their effectiveness in filling the atmosphere with dust has been amply demonstrated. The explosion of Tomboro, which killed 56,000 people in the East Indies, blew more than thirty cubic miles of material into the air. The smaller particles of this volcanic matter kept 300,000 square miles of territory in darkness for three days. The year following Tomboro's eruption has long been known as "the year without a summer." The finer dust took three years to settle. Suppose recurring outbursts kept the upper atmosphere continuously filled, year after year, with as much volcanic dust as Tomboro added to the air. How many " years without a summer " would be needed to bring

the dawn of a new ice age? One Tomboro every year or two, or the equivalent in lesser explosions, would apparently meet the requirements. We have already learned that the known ice ages followed periods of mountain building and continental uplift; we have seen that our present and recently extinct volcanoes are concentrated along the lines where the more recent diastrophic adjustments have occurred. The picture seems to put itself together.

Krakatoa produced results similar to Tomboro's. Within fifteen days after being ejected, volcanic dust thrown seventeen to thirty miles high by Krakatoa's eruption had circled the globe. Hovering aloft, their descent slowed by the same sort of action that keeps clouds composed of small droplets of liquid water from falling, the fine particles of volcanic dust enhanced the red of sunsets on a world-wide scale for nearly three years. The violence of the forces which blew this material into the air can be judged by the air waves. The sound, estimated at 190 decibels, was heard in Australia, 1750 miles away. Barometers all over the world were affected. The ocean waves created by this cataclysmic disturbance killed 36,000 people in neighboring islands of the East Indies. Nineteen years later, a slightly less violent eruption on the Island of Martinique, in the West Indies, destroyed St. Pierre and its thirty thousand inhabitants; that was the work of Pelée. In 1912, the explosion of Katmai rivaled the earlier eruption of Krakatoa. One of the largest craters of the world, a crater two and a half miles in diameter and several thousand feet deep, remains to remind us of the violence of this outburst in Alaska. Some of the material which once filled that crater has settled as a fine dust all over the world.

Theoretical considerations based on the sizes of the dust particles, their distribution in the atmosphere, and the wave lengths of sunlight and of terrestrial radiation, bear out the implications of this brief history. The effect of the dust is the reverse of the green-

house effect. Dr. Humphreys calculates that a shell of volcanic dust is approximately thirty times as effective in excluding solar radiation as it is in trapping the earth's radiation. Where the eruption occurs is immaterial, provided only that the explosion is violent enough to project the dust into the upper atmosphere; the planetary winds there distribute it over the earth.

Looking back into the immensely remote vistas of the past we are well advised to avoid dogmatism. What we can say is that there is abundant observational evidence of volcanic activity; that the relationship of diastrophic and volcanic effects, both in time and in geographical distribution, meets the requirements of the known ice ages; and that the effects contemplated by the volcanic dust theory of climatic control have actually been observed, on a small scale, far too many times to be dismissed as coincidences. Adding to volcanic action the effects produced by other purely terrestrial phenomena, especially those due to change of the ratio of land to sea area, we have at least a good start towards an understanding of climatic changes. If our brief survey of the majestic panorama of earth history has taught us anything, it is this: the earth manufactures its own history, and what has happened once, can happen again.

MATERIAL FOR REVIEW AND SELF-QUIZZING, UNIT 4

True-False Review — Appendix, Part 4.

Suggestions for Supplementary Reading and Reference

An Introduction to Physical Geology — W. J. Miller (Van Nostrand)
An Introduction to Historical Geology — W. J. Miller (Van Nostrand)
Down to Earth — Croneis and Krumbein (University of Chicago Press)
Textbook of Geology — Longwell, Knopf, Flint (Wiley)
Physics of the Air — W. J. Humphreys (McGraw-Hill)
Ice Ages — A. P. Coleman (Macmillan)
Applied Geophysics — Eve and Keys (Cambridge University Press)

Chapter 18

CONCLUSION: THE FRONTIERS OF PHYSICAL SCIENCE

EVERY science has two frontiers: one practical, the other philosophical. The practical frontier divides the realm of today's applications from what will be possible tomorrow. The philosophical frontier limits our outlook and, to a certain extent, practical applications as well. On one side of the philosophical frontier lies what is already known to be true concerning the nature of this amazing universe of matter and energy; and on the far side, either unknown or at best imperfectly known, lie other attributes which may turn up one day to astound us. In the field of practical applications the frontier is different for every science; but at the borders of knowledge the philosophical frontiers tend to merge. Whether one's chief concern is rocks or stars, electromagnetic radiation or the union of atoms, the tacit assumptions with which he approaches his problems, and his ideas of what may be possible as explanations of the phenomena in his field, are inevitably influenced by the philosophical outlook which is common to all the physical sciences.

What that outlook is, and how a serious reader who is inclined at first to insist on a reality that can be visualized, may approach it, is the theme of these few concluding remarks.

Impressive indeed has been the progress of physical science during the present generation. When the twentieth century dawned, matter and energy were thought to be separate and distinct, the one independent of the other — and so were space and time. There were two principles of conservation: one of energy, one of mass.

Light was believed to be propagated in continuous waves. Gravitation, though a law was known, was still a mystery. How the sun could control the motion of the planets across millions of miles of empty space was as completely an enigma as it had been when Newton proved that a gravitational control existed.

Today, what do we find? Matter turns into energy, and energy into mass. The two principles of conservation have merged into one. Neither is rigorously true alone; the other must be taken into account simultaneously. Relativity is established. Space and time are linked together. The curvature of the space-time continuum accounts for gravitation. To the spontaneous transmutation of a few elements, an action discovered four years before the twentieth century began, has been added artificial transmutation, a planned realization of the supposedly fantastic dream of the alchemists of the Middle Ages. One element is turned into another. Protons and deuterons are speeded up by the prodigious voltages (or their equivalent) of new machines, until they become projectiles capable of disrupting the nuclei of atoms. Electrons are dealt with as familiarly as marbles; neutrons and positrons are known. Beams of electrons produce effects hitherto thought to be reserved for light — and beams of light behave like streams of particles without losing their wave characteristics. The quantum theory of radiation is precisely as old as the present century.

A splendid array of advances, to be sure! And the list need not stop there. But suppose, instead of merely summarizing, we turn philosophers again. What single conclusion stands out as the most significant result of recent progress in the physical sciences? Of course, no hard and fast answer is possible. But consider. Space-time continuum! Curved space! Matter — substantial matter — turning itself into intangible radiant energy! Waves that are particles, and particles that are waves! Surely, we can find out some-

thing about ourselves while we are studying the nature of our physical environment. *The human mind can discover a reality which it cannot picture.* What philosophy has logically inferred, physical science proves. Whether we use the words, curved space, or something else, is not the point; the proposition still holds. To put the same idea in other words, and applying it to our own special problem, the fundamental nature of physical reality is such that it cannot be pictured in concrete graphical images.

A teleologist, a seeker after purposes, may find material for an interesting speculation in this truth; but our intent here is eminently practical, and we hurry on. The point at issue is really this: What kind of explanation is to be expected when one comes as nearly face to face with physical reality as the present state of knowledge permits? Reality is to be comprehended, if at all, by the analytical faculties. The Plato of the future, the great psychologists of a new era, the great biologists, and all other intellectual leaders who may come to grips with certain basic problems of reality, will need to be familiar with several fundamental equations. Nothing that is revealed by physics and chemistry can safely be ignored by those who study matter of any kind. All matter, living and inanimate alike, contains the nearly empty spaces which we call atoms—miniature portions of the universe marked off from completely empty space by hollow shells of energy surrounding something very concentrated, the nucleus. The Rutherford-Bohr theory, which likened the atom to a solar system, presented a picture that could be imaged by the mind, a conception at once beautiful and eminently satisfying to the graphical-minded student; but, as we saw in Chapter 10, so concrete a picture is no longer valid. Evidently a few equations are to be regarded as the only language in which the underlying nature of the material universe can be adequately expressed. That our environment con-

tains something real, something which is independent of our wishes, seems to the average physicist and chemist to be too clearly obvious to be questioned; but one who accepts the results of modern physical science can hardly believe that that reality is capable of being pictured graphically by beings who possess the same assortment of senses that we have.

So long as merely a few discoveries pointed to this conclusion, many scientists, perhaps a majority, kept those facts in separate compartments in their minds, recognizing the discrepancies but believing that further research would remove the apparent inconsistencies and restore a picturable reality. But a simple reality of that kind seems not to exist. Instead, the conclusion that the universe is not completely picturable in a graphical sense now rests on discoveries so numerous, so varied, and so tightly interlocked that it can no longer be relegated to the background.

We know, for example, that if one rushes through stagnant air he creates a stiff wind with respect to himself, but we cannot produce the corresponding effect with light. Michelson and Morley sought this effect long and carefully in 1881 and later. The idea underlying the experiment may be suggested by a special sort of swimming race. One competitor swims back and forth *across* a river, making no effort to keep from drifting downstream, while the other swims up and down. The distance across the stream is equal to the up-stream course, relative to the shore — but the up-and-down swimmer loses more time in opposing the current on the way up than he gains from the help the river gives him on his way back. If the two swimmers work steadily, at a rate that would keep them even with each other in still water, the one going up and down loses the race. A racing experiment of this kind would be a rather inconvenient method of measuring the motion of the water, but it would serve the purpose. What Michelson and Mor-

ley tried to do was to detect the earth's motion by an analogous experiment with light.

The earth, as we know, is speeding in its orbit around the sun at a rate of 18.5 miles per second. Setting up some mirrors on a grindstone floating in mercury, Michelson and Morley divided a narrow beam of light into two beams, and set them to racing each other. The path provided for one beam lay parallel to the direction of the earth's orbital motion, the other at right angles. On returning to the starting point the two beams reunited, producing dark interference bands or fringes similar to those which one can observe by looking at a distant street lamp, or a bright cloud, through a narrow slit made by holding two fingers very close together. The grindstone bearing the mirrors was then rotated in the mercury, to interchange the beams with respect to the earth's motion. One beam lost the supposed advantage of traveling across the line of the earth's motion; the other gained it. If the earth moved through a *medium* which transmitted the light waves, this transfer of an advantage from one beam to the other would be real, and the relation in which they came together when reunited would change. But there was no change! The dark fringes did not shift — and they never have shifted in similar experiments. The latest exhaustive test was made in 1929. If light behaved in accordance with simple mechanical concepts, the effect would have been twenty times as great as the smallest that the Michelson-Morley apparatus was prepared to reveal.

Einstein drew the logical conclusion from this result. No matter how fast we rush towards a source of light, or away from it, even at speeds as great as the earth's speed in its orbit, the light from the source passes us at the same rate, 186,285 miles per second. Even if the observer were to run away from the source of light at a speed of 186,285 miles per second, the rays of light which

it sent after him apparently would not only overtake him, but *pass him at the same rate as if he were standing still* with respect to the source, or even approaching it with the speed of light. This is a disturbing result — but here we are concerned with two points, only. *First,* the discovery of this surprising behavior of light is the starting point of relativity; and *second,* a theory of physical reality which starts with a result so different from what one might predict on the basis of experiments with gross objects, say a baseball thrown after a rapidly retreating train, may be expected to lead to other amazing conclusions.

Results of this nature have multiplied. We inhabit a universe in which time should apparently be regarded as a fourth dimension. Such a world does not lend itself to graphical picturing by one whose senses inform him of three dimensions, only: length, breadth and thickness. Analogies of infinitely thin insects crawling on a two-dimensional surface of paper, unaware of the third dimension of height, may help to remind us that there may be a fourth; but they do not alter the fact that man can form images in no more than three dimensions. One can draw an X-axis, a Y-axis and a Z-axis mutually at right angles, like the three edges that intersect the corner of a soap box; but when he tries to add a fourth axis, he finds that there simply isn't any room left. An equation may contain as many dimensions as we choose; a picture cannot.

The situation in respect to the curvature of space is somewhat similar. To speak of a curved tree arouses an immediate image in the mind; to speak of curved space does not. Einstein proposed the concept of curved space in an effort to account for something that had never been explained: the existence of gravitational forces. Here was one of the major mysteries — and to have solved it, even if the answer is not as simple as an adventure with Archi-

medes' principle, is one of the great triumphs of this generation. To one who demands picturable situations, curved space is no easier to accept than the original mystery of a force which somehow reaches out through millions of miles of vacuum to keep the earth imprisoned in its orbit; but this does not prevent the concept from finding its counterpart in nature. Einstein showed that his idea accounted for an unexplained discrepancy in Mercury's motion.

The orbit of Mercury is a rather elongated oval, or ellipse. In addition to the motion of Mercury around this orbit, the orbit itself rotates slowly around the sun (if one may speak of an orbit as rotating). Thus Mercury is obliged to make slightly more than one complete revolution around the sun in order to return to that point in its orbit which is closest to the sun. This effect (known as the advance of the perihelion) is partly due to the attraction of the other planets; but the part that cannot be accounted for by all the known planets is so large that astronomers, remembering how Leverrier discovered Neptune without seeing it and thus solved the mystery of Uranus, had long sought for a new planet to explain the mystery of Mercury. Some were so confident that they named it Vulcan in advance. But Vulcan was strangely modest: it never appeared! For great distances and nearly circular orbits, Einstein's law of gravitation reduces to Newton's; but for Mercury, whose orbit lies close to the sun, and is elongated, the difference between the two laws is appreciable. The agreement between observation and Einstein's calculation is as 42 to 41 — a triumph for a new view of gravitation.

The idea that what seems to be a force — one's own weight, for example; the same force that may bring a person crashing to the ground from a treetop — is due to a curvature of *space,* is so disquieting to anyone who has depended largely on his senses for his

views of nature, that he can hardly help wondering how such an idea may have suggested itself to Einstein. The idea is bound up with acceleration. A person in an elevator *seems* to weigh more at the instant the elevator starts up; for the floor must press with an extra force against his feet to accelerate him upwards. If the elevator were to continue indefinitely to rise faster and faster, the occupant would be continually subjected to this extra pressure of the floor. If he dropped his hat, it would seem to fall faster than ordinarily expected; because the floor would gain speed upwards while the hat was in the air, and the owner would not distinguish between an upward acceleration of the floor to meet the hat, and a downward acceleration of the hat to meet the floor. Obviously, acceleration *in a straight line* could not account for weight in general. The earth could not be accelerating in all directions simultaneously. But motion in a *curved path* produces what is commonly called centrifugal force. The acceleration of a body going around a curve is directed towards the center of the curve. Einstein's idea is that the presence of matter curves space in such a way as to produce the force known as gravitational attraction.

Further, believing that energy and mass are of essentially the same nature, in the sense that one may be converted into the other, Einstein predicted that light would be found to be subject to gravitational attraction. Here was another revolutionary idea — and Einstein committed himself in advance to *two* predictions. With his equations before him he predicted that starlight passing close to the sun on its way to us would be deflected. The deflection was looked for during the total eclipses of 1919, 1922, and subsequently, when the stars beyond the sun could be seen. Telescopic photographs of stars in the direction of the sun showed apparent displacements which agreed, both in direction and in amount, with Einstein's predictions.

The *second* prediction introduces us to one of the most remarkable stars. Sirius, the brightest star in the sky, has a faint companion which revolves around it once every fifty years. It is so hot that if it were of average size, it would be an extraordinarily brilliant object. But it is an exception even among dwarfs. The distance through its center is not more than three or four times as great as the earth's diameter. The matter which composes it is almost unimaginably compact. It is about fifty thousand times as dense as water. A cubic inch of material as dense as that, resting on one of our terrestrial desks as a paperweight, would defy the efforts of any man to lift it without machines. It would weigh three-quarters of a ton. With its small size and great mass, this faint companion of Sirius is ideally adapted to test Einstein's prediction that light, being subject to gravitational attraction, *will tend to be held back slightly by the body which radiates it.* The effect, he calculated, would reveal itself as a shift of the Fraunhofer lines away from their familiar places in the spectrum — a shift towards the red end. This prediction, too, has been confirmed by observation.

We have room for only a few glimpses into the frontier regions of physical science, but even these few should make the thesis of the chapter clear. That species of reasoning called common sense may often have retarded science for a while, but in the end scientific reasoning prevails. The conversion of matter into radiant energy, an action which was presupposed in the preceding chapter when we referred to the probable duration of the sun, is a familiar idea today — but to an exponent of common sense, a star which gradually dissolves into intangible radiation is accomplishing a feat little short of a miracle. True, water disappears when it evaporates; but the picturing mind is content with the knowledge that the invisible vapor, if collected and condensed, would again fill the dish

with space-occupying matter of satisfying substantiality. The matter which is converted into radiant energy is not, so far as we know now, rematerialized. There are good grounds for believing that in certain recent experiments some radiant energy (gamma rays) has been converted into electrons and positrons, but the question remains in doubt—and as for what becomes of all the sunlight that travels on and onward past the stars, we simply do not know.

Even the means by which the light is propagated is, in one sense of the word, a mystery. Walking in the sunlight or under the twinkling stars, we observe the effects of electromagnetic waves which are propagated through space where there is nothing material to do the waving; to say that we can *picture* the process is to delude ourselves. We know the equations of the propagation; we believe that the successive magnetic effects in the step-by-step progress of the radiation occur at right angles to the electric effects which are sandwiched between them; and we can predict the results with impressive certainty. But graphic imagery of the action fails us. There is no matter there to wave in response. The equations, and apparently they alone, tell the story of the propagation.

But equations have not figured prominently in our pages. How, then, can it be that a few matters have seemed to be clear? It is partly because the more puzzling aspects of physical reality which we are summarizing in this section seldom need to be taken into account in practical matters, or even in experiments of the sort that a student, an engineer, or a scientist would ordinarily perform unless he was purposely seeking to penetrate to the frontiers of his field. And through most of the discussion the familiar language of cause and effect has appeared—a language which assumes that establishing one set of conditions *produces* a certain result. The thinker who is operating at the frontier is likely to substitute *proba-*

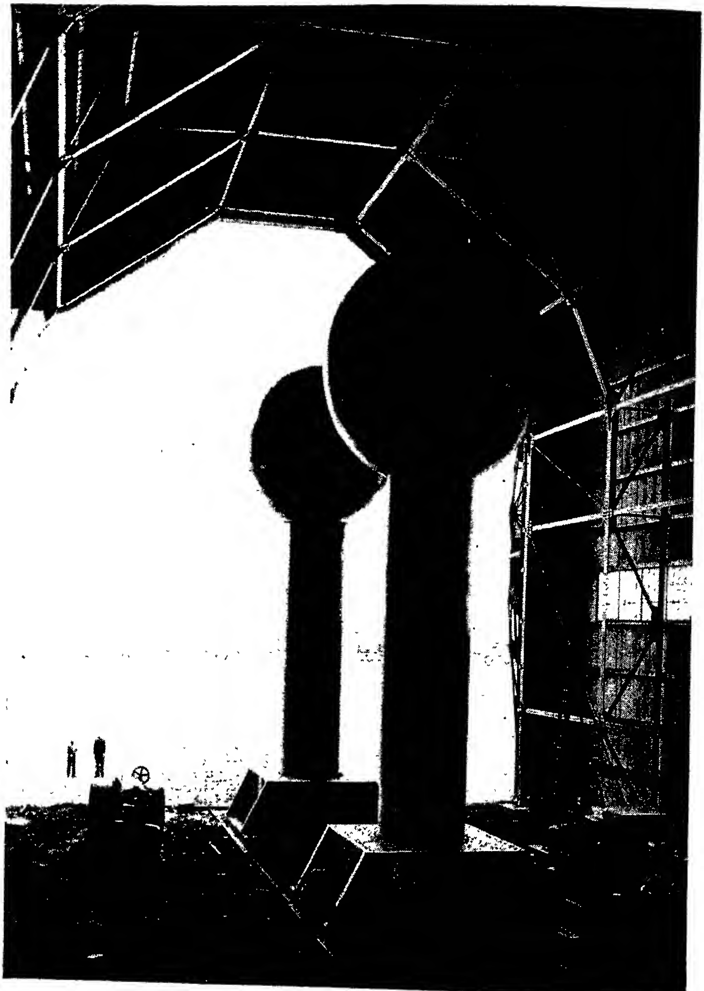


FIGURE 78. The Van de Graaff electrostatic generator. The tremendous voltages obtainable with this device are useful in subatomic research and find practical application as well. Recently, the principle was used by Professor John G. Trump in designing a million-volt x-ray installation capable of producing a highly penetrating radiation surpassing in intensity the gamma-ray output of all the radium yet refined. (Photograph courtesy Professor R. J. Van de Graaff.)

bility for cause and effect. He sees an occurrence, not as the inevitable result of a *cause,* but as merely the most probable of a number of possible results. From a practical point of view the distinction is negligible, since those other possibilities, those violations of laws, are never observed when relatively large numbers of atoms or electrons are being dealt with. Philosophically, however, the idea may be important. It denies complete determinism, for one thing, and may also be applicable to enigmas such as the one which we came upon when wondering why a certain thirteen of the radium atoms in a million million explode in a given second instead of some other thirteen. There is even a *principle of uncertainty* to be found in recent literature. Heisenberg was led to state this principle by the discovery that it is apparently impossible to determine *both* the position and the velocity of an electron at the same time.

We are not trying to build up a catalogue of marvels in these few concluding words. All we seek here is a sensible approach. So many able students (usually the ablest students) have racked their brains in vain efforts to *picture* something which by its very nature transcends our powers of imagery, that to admit the limitations of the human mind seems the only wise course to adopt. Will that admission lead any serious reader to minimize the importance of the conclusions to which a great mass of experimental findings point? May we not still picture what is picturable, trust our analytical faculties for the remaining truths—and all the while enjoy the thought that a universe whose basic mysteries are so well hidden from the eye is yielding up its secrets, one by one, to the *combined* faculties of man?

The results, by any measure, give the philosopher plenty of grist for his mill. In Unit 2 we ventured into the interior of the atom. Today, the nuclei of atoms are being taken apart in several

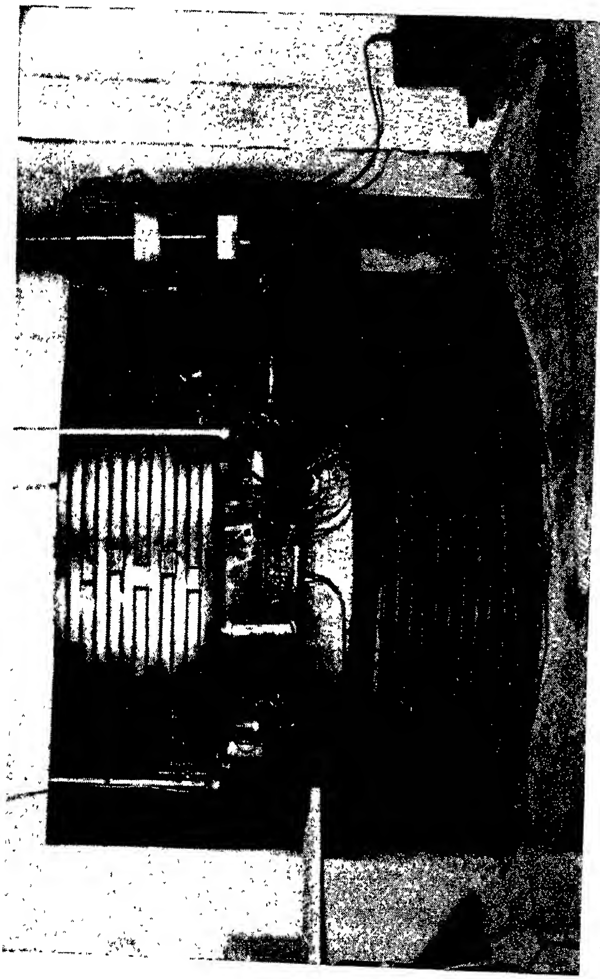


FIGURE 79. The cyclotron. This atom-disrupting apparatus was recently installed in the University of Michigan under the direction of Professor H. M. Randall and Professor James M. Cork.

laboratories. Few elements remain which have not been transmuted into other elements. Alpha rays may be used in this work of transmutation, but protons and deuterons artificially speeded up are rapidly superseding them. Protons are obtained by stripping away the outer electrons of the atoms of ordinary hydrogen, to bare the nuclei. Similarly, deuterons are secured by stripping (ionizing) heavy hydrogen. To obtain the protons or deuterons is easy; but to enable them to penetrate to the nuclei of other atoms, the ones to be disrupted, we must give them tremendous velocities. Two nuclei, since both are positively charged, repel each other; the repulsion must be conquered by high speed.

Van de Graaff's electrostatic generator supplies voltages of several millions, which can give the protons and deuterons the necessary speeds; and in the *cyclotron,* E. O. Lawrence's marvelous recent invention, the *effect* of millions of volts is obtained at the expense of a few thousand. The cyclotron has two broad magnet poles to curve the paths of the protons. Round and round in a vacuum, between the pancake-shaped magnet poles, a proton whirls, following an ever-widening spiral path. An electron tube automatically reverses the voltage several million times a second — once for every time the proton completes a half-circuit. Thus *twice* in every revolution it receives the full accelerating effect of the voltage. If the voltage is 50,000, and the proton completes 50 circuits (100 half-circuits) before darting away to perform its work of disruption, it receives an energy of 100 times 50,000, or five million of the units called electron-volts. The 50,000 volts have served as well as five million — and the protons have become projectiles equal to the task of transmutation. A broad beam of protons or deuterons, each carrying the energy of six million electron-volts, can plunge through twelve inches of the atmosphere after passing through a solid metal window which seals the vacuum.

FIGURE 80. A beam of deuterons in the open air. The deuterons producing this intensely luminous display are the atomic nuclei of heavy hydrogen, and they emerge from the Lawrence cyclotron with nearly six million electron-volts of energy. The method devised by Professor Ernest O. Lawrence makes transmutation of elements possible without requiring excessive voltages. A moderate voltage is applied to the deuterons or protons over and over again as they circulate in an ever-widening spiral path in the pancake-shaped vacuum chamber between the poles of the huge magnet, until finally they emerge at the end of the spiral with as much energy as a single application of several million volts would have given them. (Photograph courtesy D. Cooksey, University of California.)

The air will become intensely luminous. The distant future may hold the prospect of gold and other elements made economically by transmutation — but there is none to be found now unless one can read the instruments of the scientist.

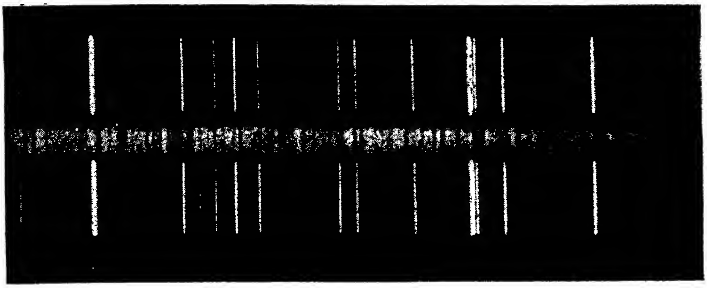


FIGURE 81. The spectrum of Procyon, with a comparison spectrum above and below to reveal the displacement of the star's spectrum towards the blue (right). A shift towards the blue indicates approach; towards the red, recession. Some stars are approaching us. Others, including most of the exterior galaxies, are receding at great speeds. (Photographed at Lowell Observatory.)

This recent work of transmutation stands at the frontier of physical science. The atoms of a number of elements have been found to continue to disintegrate after having once been struck. This is artificially induced radioactivity. The nuclei are hard to hit. Thousands of protons may plunge through an atom before one lucky shot smashes home to the nucleus. Atoms are mostly empty space — and the nucleus is hidden away at the center. There, if we may use the word in a two-fold sense, is one of the frontiers of physical science. But science deals with the great as well as the small, and there is another frontier. Suppose now, to complete a contrast, we look outward to the celestial frontier, to the farthest stars yet studied.

Strewn through the heavens are thousands of stars of a certain

variable type known as *Cepheids.* Their brightness regularly waxes and wanes. These stars are apparently pulsating — expanding and contracting. The apparent brightness, or visual magnitude, of a star depends on its actual luminosity and its distance from us. The luminosity can be calculated as soon as we know the star's distance and its apparent brightness. In 1912, making the calculations for Cepheid variable stars whose distances could be determined directly by a method based on angles, Miss H. S. Leavitt of Harvard discovered a relation. The rate at which a Cepheid variable star pulsates depends on its luminosity. One which surpasses our sun in luminosity by a hundred-fold completes a cycle of change in about twenty-four hours; another ten times more luminous still, or a thousand times as luminous as the sun, requires about ten days to pass from one maximum of brightness to the next. In the hands of Harlow Shapley, this relation soon became one of the astronomer's most powerful tools for sounding the depths of space. A Cepheid variable can be recognized wherever it appears; the length of time required for a cycle of change reveals its actual luminosity. It is then easy to calculate how far away the star must be in order to appear as faint as it does.

The imagination falters before the universe which recent measurements reveal. Our galaxy, including the Milky Way, turns out to be merely one of many galaxies in space. It is approximately 100,000 light-years in diameter. Within this galaxy the sun, carrying its family of planets with it, is speeding towards Hercules at a rate of approximately twelve miles a second. The whole galaxy of stars is also rotating, and the rotation, which requires about 200,000,000 years to carry us once around the center of the galaxy, gives the sun, earth and all the other planets an extra speed of 150 to 200 miles per second. Yet this galaxy of ours, with its nearly a billion counted stars and doubtless additional billions still to be

FIGURE 82. Great Nebula in Andromeda, approximately 900,000 light-years distant. This is one of many galaxies far beyond our own. (Photographed by G. W. Ritchey, Yerkes Observatory.)

detected, is merely one of hundreds of similar galaxies. The Great Nebula in Andromeda — to the naked eye a faint spot barely bright enough to be detected — is itself a great spiral galaxy of stars, a galaxy so large that a ray of light would require 40,000 to 80,000 years to cross it, and so far from us (900,000 light-years) that, viewed from anywhere within it, the Milky Way would be merely a faint spot in the heavens.

Far beyond the Great Nebula in Andromeda, to a maximum distance, roughly, of half a billion light-years, other galaxies have been detected. Even so, one hears the question: "Is the universe expanding?" Analyzing starlight with the spectroscope, the astronomer finds dark (Fraunhofer) lines, the same sort of lines which, in the sun's spectrum, show what chemical elements there are in the sun's atmosphere. Each chemical absorbs most strongly its own characteristic wave lengths of light. These tremendously remote galaxies contain elements with which we are familiar. But more to our present purpose, the Fraunhofer lines are displaced whenever the distance between the earth and the star is changing. Just as the rapid approach of a whistling locomotive crowds a few extra sound waves into the ear every second, raising the pitch, so the rapid approach of a star shifts all the lines in its spectrum slightly towards the blue. If the star is receding, the lines are shifted towards the red. The velocity can be calculated from the amount of shift. A surprising result is found. The outer galaxies seem to be receding from us at speeds ranging upwards to thousands of miles a second. Hence the familiar expression, "the exploding universe." But a note of caution should be sounded here. Some other cause, some action not yet understood, may help to produce the redward shift as the light travels through the great stretches of interstellar space.

It is a long way out to those receding galaxies of stars. The

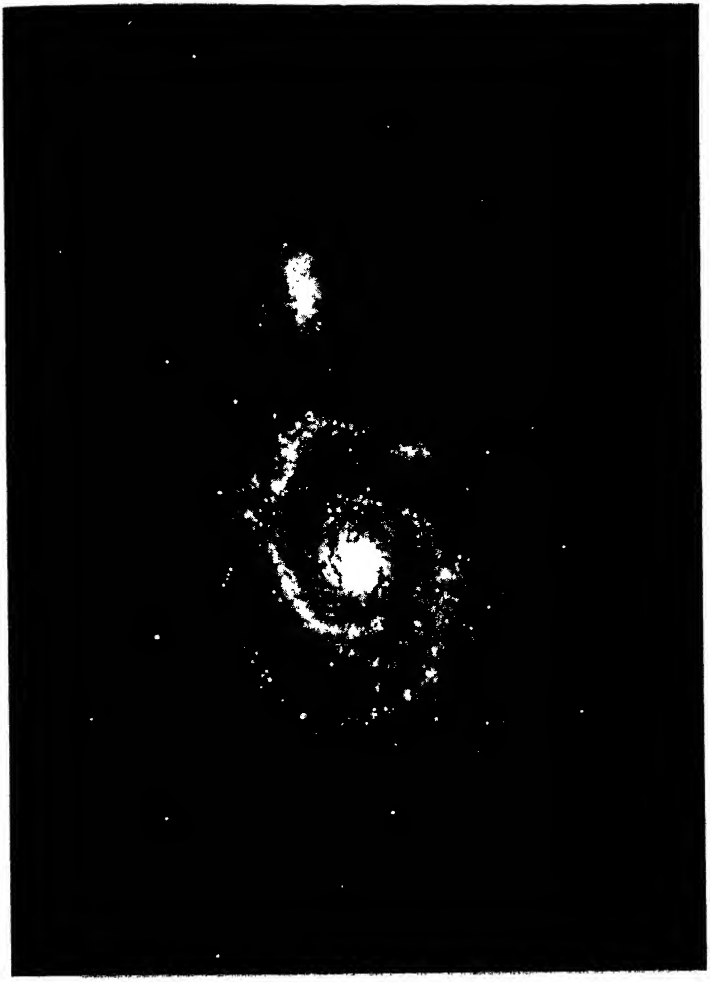


FIGURE 83. An exterior galaxy: Spiral Nebula M51. (Photographed at Mount Wilson Observatory.)

earth seems dwarfed, a mote moving in the sunbeam, undetectable from even the nearest star of our own galaxy. But the earth is the abode of man. Can man be less than all he knows? By the time scale of the one-hour motion picture of condensed earth history which we imagined in the preceding chapter, the whole of physical science has been built up in less than half of the last one-hundredth of a second of the one-hour showing time. How much more will be known when half of the next hundredth of a second has rolled around?

Supplementary Reading

The Renaissance of Physics — Karl K. Darrow (Macmillan)
Development of Physical Thought — Loeb and Adams (Wiley)
The Mysterious Universe — Sir James Jeans (Macmillan)
New Pathways in Science — Sir Arthur Eddington (Macmillan)
The Nature of the Physical World — Arthur Eddington (Macmillan)

ASTRONOMICAL SUPPLEMENT

OBSERVER'S GUIDE TO THE HEAVENS

Jupiter
Saturn
The Earth as Viewed from Saturn
Uranus, Neptune and Pluto
Eclipses of the Sun and Moon

RECOGNIZING THE STARS AND PLANETS

Our concluding pages are devoted to the interests of those enthusiastic students of nature who have no time to master the details of technical astronomy yet do not wish to deprive themselves of the lasting satisfaction that springs from even a moderate familiarity with the wonders of the sky. "Why did not someone teach me the constellations and make me at home in the starry heavens . . . ?" cried Thomas Carlyle. It is a common lament — yet how easily one can make himself at home in the heavens if he will only learn a few landmarks (or rather skymarks) to begin with.

In earlier chapters we have studied the fundamental physical principles which the heavenly bodies obey as they move past us. Interesting facts about the sun, moon, stars, and planets have come to light by way of illustration. Now, on turning the page, the reader will find two tables which summarize many facts concerning individual planets and stars; and following that, one comes on a succession of short articles designed to afford the observer a varied sampling of the heavens. The emphasis is placed on what can be learned with the naked eye and with a telescope of moderate size; but since observing becomes much more interesting once one has a background of information about the objects studied, the articles go considerably beyond mere practical advice for the observer.

CONSTELLATIONS

Table 1, dealing with the planets, is self-explanatory. Some of the headings of Table 2, however, require a few words. The stars are at different distances from us, but our eyes, giving no perspective in space, see them as groups or constellations; e.g., Orion, Cas-

FIGURE 84. Members of the student telescope team at Florida State College for Women adjusting a portable 5⅜ inch refractor preparatory to a study of sunspots. The polarizing eyepiece to dim the sun's image to any brightness desired is attached.

siopeia, Perseus. The grouping of the stars is apparent, in most cases, not real: if we were located elsewhere in the universe the arrangement would appear quite different. Two stars appear close together if they are nearly in the same line of sight; actually, one may be hundreds or thousands of light-years beyond the other. But since all the stars are so remote that their high speeds do not cause a noticeable change of position in the course of a few centuries, the constellations may be considered fixed and should be recognized by their shapes, their relative positions, or by conspicuous objects which lie within them. There are ninety all-told, but to learn twenty of the more prominent ones makes a good start.

TABLE 1. THE NINE PLANETS

Planet	Millions of Miles from Sun (Mean)	Revolves Around Sun in (Yrs.)	Mass Compared with Earth	Surface Gravity Compared with Earth
Mercury	35.96	0.241	? 0.04	? 0.27
Venus	67.20	0.615	? 0.81	? 0.88
Earth	92.90	1.000	1.000	1.00
Mars	141.54	1.881	0.108	0.38
Jupiter	483.31	11.862	316.94	2.64
Saturn	886.12	29.458	94.92	1.19
Uranus	1782.70	84.015	14.58	0.96
Neptune	2793.40	164.788	16.93	0.98
Pluto	3680	249	Smaller	?
Planet	**Mean Diameter (Miles)**	**Rotates on Axis in**	**Number of Moons**	**Velocity in Orbit (Mi/Sec)**
Mercury	3,009	? 88 days	0	29.7
Venus	7,575	?	0	21.7
Earth	7,918	23.93 hrs.	1	18.5
Mars	4,216	24.60 "	2	15.0
Jupiter	86,728	9.9 "	9	8.1
Saturn	71,500	10.2 "	9	6.0
Uranus	30,878	10.7 "?	4	4.2
Neptune	32,932	15.0 "?	1	3.4
Pluto	Small	?	?	2.9

TABLE 2. THE TWENTY STARS NEARER FIRST MAGNITUDE THAN SECOND

Star Name	Name of Constellation	Magnitude	Distance in Light Years	Luminosity Compared with Sun	Velocity towards or from (T or F) Sun (Mi/Sec)	On Meridian about 8:30 P.M.	
						Date	Degrees North or South of Zenith at 40° North Latitude
Sirius	Canis Major	− 1.58	8.8	26.3	T 5.3	Feb. 20	S 57
Canopus	Carina	− 0.86	600 ?	80,000 ?	F 12.4	Feb. 13	S 93
Alpha Centauri	Centaurus	0.06	4.3	1.3	T 13.7	June 18	S 101
Vega	Lyra	0.14	26	50	T 8.5	Aug. 19	S 2
Capella	Auriga	0.21	52	165	F 19.3	Jan. 25	N 5
Arcturus	Boötes	0.24	41	100	T 3.1	June 13	S 21
Rigel	Orion	0.34	500	16,000 ?	F 13.9	Jan. 25	S 49
Procyon	Canis Minor	0.48	10.5	5.5	T 2.5	Mar. 3	S 35
Achernar	Eridanus	0.60	70	200	F 10.0	Dec. 5	S 98
Beta Centauri	Centaurus	0.86	300	3,100	F 2.5	June 10	S 100
Altair	Aquila	0.89	16	9.2	T 20.5	Sept. 8	S 32
Betelgeuse	Orion	0.92	200	1,200	F 13.0	Feb. 4	S 33
Alpha Crucis	Crux	1.05	230	1,650	F 4.3	May 18	S 103
Aldebaran	Taurus	1.06	57	90	F 34.2	Jan. 15	S 24
Pollux	Gemini	1.21	32	28	F 2.4	Mar. 4	S 12
Spica	Virgo	1.21	230	1,500	F 1.2	June 1	S 51
Antares	Scorpius	1.22	380	3,400	T 1.9	July 16	S 67
Fomalhaut	Piscis Australis	1.29	24	13.5	F 4.2	Oct. 28	S 70
Deneb	Cygnus	1.33	600 ?	10,000 ?	T 2.5	Sept. 23	N 5
Regulus	Leo	1.34	56	70	F 5.0	Apr. 12	S 28

STAR MAGNITUDES

The visual brightness of a star is commonly expressed in magnitudes. The 5000 stars which can be seen with the naked eye (but not quite half that many at one time) have been divided arbitrarily into six magnitudes. The 20 brightest constitute the first magnitude; and the faintest detectable without optical assistance, the sixth. Measurements reveal that the first group, thus defined, averages 100 times as bright as the sixth.

Upon this arbitrary foundation a system of designating star-brightnesses has been erected. The peculiarities of the eye are taken into account. For instance, doubling the amount of light emitted by a source does not make it appear twice as bright. Weber's general law of sensations is: When the stimulus increases in geometrical progression, the resulting sensation increases in arithmetical progression; i.e., much more slowly. Thus if the stars of the first magnitude are to appear as much brighter than the second, as the second appear brighter than the third, then, in terms of light received by the eye, the first must surpass the second by as many *times* as the second exceeds the third. And so on. The factor we must use to make the sixth magnitude 100 times as bright as the first is 2.512, because 2.512 x 2.512 x 2.512 x 2.512 x 2.512 equals 100. The typical star of one magnitude gives us 2.512 times as much light as one of the next fainter magnitude.

The system has been extended to stars which are invisible to the unaided eye. Twenty-one magnitudes including more than one billion stars lie within the photographic reach of the greatest modern telescopes. The brightnesses of the twenty brightest stars are given in Table 2. Zero-magnitude represents a star which is 2.512 times as bright as one of magnitude 1.0, and a negative magnitude indicates that the star is even brighter than that. Please note that

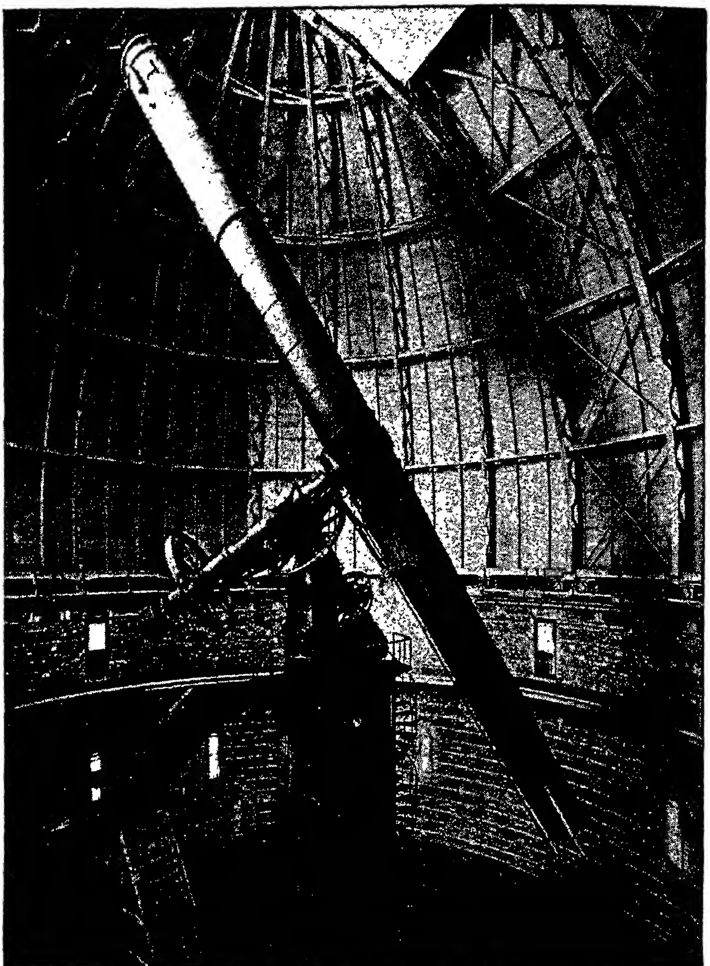


FIGURE 85. World's largest *refracting* telescope. Yerkes Observatory. The objective lenses are 40 inches in diameter.

magnitude does not mean size. Neither the eye nor any telescope gives any immediate indication of star sizes. The student of physics should also note that we have used *brightness* in the usual astronomical sense. Strictly speaking, the brightness of a star would signify the amount of light emitted per unit area of its surface, but we use the common meaning of the word here.

LIGHT-YEARS

The distances of the stars are so great that a long yardstick, the light-year, is convenient. In free space light travels 186,285 miles per second — 5,875,000,000,000 miles in a year. Multiply that enormous figure by the number of years light requires to reach us from a given star and you have the star's distance in miles.

LUMINOSITY

The apparent brightness of a star depends on two quantities: how much light it actually emits, and how far away it is. The first quantity is known as the luminosity of the star. Note Sirius, for example, the Dog Star, in the constellation Canis Major. The magnitude column of Table 2 shows that Sirius appears much brighter than Antares, although we see in the luminosity column that Antares far surpasses Sirius in intrinsic luminosity. Sirius radiates 26.3 times as much light as our sun, but Antares shines with the luminosity of 3400 suns. How hot the earth would be if Antares were our sun, a mere 93,000,000 miles away! But we couldn't be as close as that to the center of Antares without being inside of it. The diameter of this red-hot giant is 390,000,000 miles. Finishing our problem, we find in the distance column the reason why Antares, despite its vastly greater luminosity, does not appear

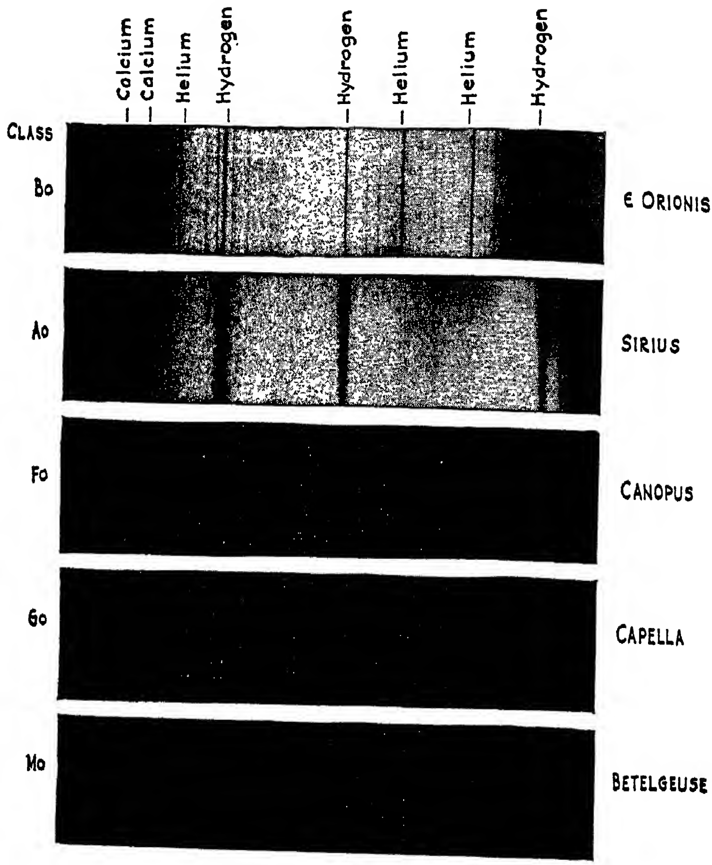


FIGURE 86. Star spectra. Analysis of the spectra aids the astronomer in classifying stars. Lines corresponding to chemical elements with which we are familiar appear in the star spectra. (Photographed at Harvard Observatory.)

as bright as Sirius. Sirius is 8.8 light-years distant, Antares 380. We see Antares as it was before Galileo founded modern science. What has happened to it in the meantime, if anything, future generations will find out when the telltale light gets here.

VELOCITIES OF THE STARS

By spectroscopic methods the speeds and directions of motion of the stars, relative to the sun, can be determined. In Table 2 we give only that component of the velocity which measures how rapidly the star is approaching us, or receding. Sirius, for example, is coming nearer at the rate of 5.3 miles per second — but although already nearer to us than any other star visible at latitudes north of New Orleans it can continue to rush towards our corner of the galaxy at that rate for many centuries without getting appreciably closer or appearing much brighter.

WHEN TO LOOK FOR CERTAIN STARS

The last two columns of Table 2 show at a glance when the observer may expect to find a given first-magnitude star high in the heavens. The next-to-the-last column gives the date on which the star in question will cross the meridian at about 8:30 P.M. The meridian is simply the arc of a circle drawn through the sky north and south and passing through the point overhead, the zenith. The lazy man's way of making the acquaintance of the first-magnitude stars would be to go out at 8:30 P.M. on the dates in question, look north or south of the zenith the number of degrees indicated, and thus in the course of a year locate all the first-magnitude stars which are not too far south to be seen from his latitude.

A few precautions should be observed in using the table. The stars will be as far north or south of the zenith as shown if one observes from points near the forty-degree latitude line running through the country east and west. This passes close to New York; Pittsburgh; Columbus, Ohio; Indianapolis; Springfield, Illinois; Kansas City; Denver; Reno; Sacramento. If the observer is farther north than one of those cities, the stars will appear farther south than indicated; and if he lives farther south, the stars will appear farther north. But since no part of the United States except the extreme southern regions of Texas and Louisiana, and of course most of Florida, is more than ten degrees from the latitude line for which the table has been made, the stars will be nearly as far north or south as indicated, within a very few degrees. Also, for most locations, the reading of a clock when the star reaches the meridian will not agree exactly with the time given, 8:30 P.M. This is because standard time is correct, astronomically speaking, for only the appropriate longitude. But the error will not be more than a half-hour either way unless the city is using the standard time of the zone next to its own; and in half an hour a star moves only seven and a half degrees. The upshot of all this is that to within a few degrees this simple method of identifying the stars is practicable anywhere in the United States.

Deneb, Vega, Altair. Let us take an example especially applicable to the beginning of the college year. The table states that Deneb, the bright star at the head of the dagger-like Northern Cross (constellation Cygnus, the Swan) will be on the meridian at about 8:30 P.M. September 23 and will lie 5 degrees north of the zenith. Going out into the open at that time we stretch an arm directly overhead and then drop it northward through an angle of 5 degrees, which is a mere one-eighteenth of the whole angle down to the horizon. We find it pointing to Deneb. We need

Figure 87. Ring Nebula in Lyra. Compare the images obtained with the 60-inch and the 100-inch telescopes at Mount Wilson.

only moderate accuracy: there is little danger of confusing a first-magnitude star with a faint one. A week earlier or later would find the star slightly east or west of the meridian; for, as we saw when considering the earth's rotation, the stars rise about 4 minutes earlier every night and thus reach the meridian 4 minutes earlier.

Rounding out our example, we see by the table that two other first-magnitude stars must be near Deneb. Vega lies 2 degrees south of the zenith on August 19, and Altair 32 degrees south on September 8. Both those dates are close enough to September 23 to ensure that the stars will not be very far from the meridian. Since Vega reached the meridian at 8:30 about a month earlier it will now be about 30 degrees farther west — for every star must gain enough every month to make the whole 360 degrees around the pole of the heavens in 12 months. Altair reached the meridian at 8:30 about two weeks earlier, so will be slightly west but not as far as Vega.

We see that these three first-magnitude stars cannot be far apart. All are high in the heavens at 8:30 P.M. September 23. Deneb is slightly north of the zenith; Vega is slightly south; Altair is quite a bit south. Deneb is on the meridian, neither east nor west; Vega is farthest west, Altair is slightly west. Thus we easily establish a fine group of skymarks — and by consulting a star-chart or the *Monthly Evening Sky Map* we can extend our acquaintance to objects which are near this group.

Identifying Vega. As soon as you think you have identified the group, make sure by putting the binoculars on Vega. This beautiful star carries its own identification with it — two faint stars visible to the naked eye, forming with Vega an equilateral triangle, and one of them a close pair seen distinctly as a double even under low magnification. The whole triangle can be seen in the binoculars' field of view at one time.

Southern Stars Invisible Here. One further point of interest we note before leaving Table 2 for the reader's use and study throughout the year. Running down the last column we find that five of the stars are more than 90 degrees south of the zenith. They are therefore below the horizon of a person who lives near latitude 40 degrees north even when highest, and can never be seen. This leaves fifteen of the twenty first-magnitude stars to be seen from latitude forty degrees north at suitable times during the year. By observing from points as far south as New Orleans or Miami one can add several of the missing five to his repertoire. Most of the twenty first-magnitude stars, then, can be seen from the United States at the appropriate times and the reader who does not already recognize them should enjoy coming to know them as the year progresses.

THE POLAR GROUP OF STARS

Polaris, the North Star, is a second-magnitude star which dominates its vicinity. It is approximately 450 light-years distant and shines with the luminosity of about 2500 of our suns. If the sun were as far as Polaris it would appear of magnitude 10.8 — a dim, telescopic object nearly five magnitudes fainter than the faintest naked-eye objects. Polaris is attended by a faint ninth-magnitude companion which is difficult to find with small telescopes because it lies so close to Polaris.

Ursa Major, Ursa Minor, Cassiopeia. Polaris is easily located. (1) Look above the north horizon at an angle equal to the latitude of the locality. (2) Polaris completes the little dipper (Ursa Minor, the lesser bear). The little dipper swings as if Polaris were the nail through the hole in the end of the handle. The curved handle is formed of faint stars, but the outer side of the cup contains two bright ones called the Guardians of the Pole. (3) The outer edge

of the cup of the big dipper (Ursa Major, the greater bear) points to Polaris. These pointers are about 5 degrees apart; from there on to Polaris is 30 degrees. For most of the United States, the big dipper never sets; but during autumn in the southernmost tier of states, the cup of the dipper spends most of the night below the real horizon. The handle can be seen then, however, and the cup can be inferred from the fact that the big and little dippers are always so placed that one pours into the other. (4) Cassiopeia, the woman in the chair, forms a huge "W" whose open top faces towards Polaris. (5) Finally, Polaris is the star which, as explained in Chapter 3, seems to stand still while the others revolve around it. An hour or two of observation, or a camera left focused on Polaris brings this out clearly.

MIZAR AND ALCOR

A quick glance at Ursa Major, the Big Dipper, shows nothing of great interest except the shape. The seven second-magnitude stars which mark the outline of this familiar constellation seem to be mere points of light important only for their arrangement. Closer study reveals surprising facts. Indeed, one need only examine the bend of the handle to become aware of the magnificence of the universe. For nearly three centuries astronomers have been studying the complexities of the objects which mark the bend.

To astronomers, the star at the bend of the handle is Zeta of Ursa Major. Laymen know it by its Arabian name, Mizar. Close to Mizar lies a lesser star, so close that the Arabians named it Alcor, meaning "The Test" — a test for eyesight. Alcor is of the fourth magnitude, brighter by two magnitudes than the faintest stars visible to the naked eye. It is separated from Mizar by less than a fifth of one degree — 11.5 minutes of arc — but these two stars

are so far from us (about 75 light-years) that this small angle means a separation of at least 15,000 times the distance from the earth to the sun.

Try separating Mizar and Alcor with the naked eye. What may

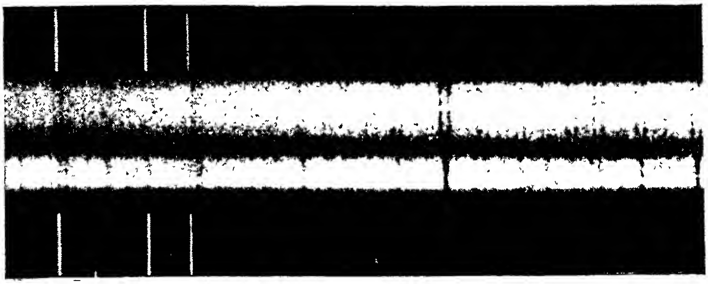


FIGURE 88. Two spectra of Mizar, with bright-line comparison spectrum above and below. The alternate doubling and closing of the lines reveal the existence of two stars too close to be separated with a telescope, one revolving around the other. (Photographed at Mount Wilson Observatory.)

have been an exacting test for the Arabians of the desert some centuries ago, is no test for a normal eye now. Put the field glasses on Mizar and watch Alcor jump away under the magnifying power. The angular distance between Mizar and Alcor is approximately six times as great as the discrepancy in the position of Uranus which led Leverrier to discover Neptune, and it is about twice as great as a certain disagreement which caused Kepler to discard a promising hypothesis and continue his work until he found the true laws of planetary motion. To remember these facts when studying Mizar and Alcor with the instruments will aid in appreciating the accuracy with which astronomers regularly observe and draw conclusions.

Now try the telescope. Unless an extremely low power is used Alcor will be outside the field of view. We are studying Mizar

alone now, and we find that it itself is a double star. Its two components are of nearly equal brightness, 14.6 seconds apart. This means a real separation of 30,000,000,000 miles, or more than 300 times the distance from the earth to the sun. And we had to use a telescope to detect that great distance! One begins to appreciate how remote the stars are when he finds that a telescope is required to separate two stars which are as far apart as that.

Spectroscopic studies have shown that this is only the beginning of a splendid story. *Each* of the two components of Mizar is itself a double star. The brighter component consists of two suns only 14,000,000 miles apart—much closer to each other than the earth is to the sun. These two stars revolve about their common center of gravity once every 20.5 days. Their combined mass is several times that of the sun. The lesser component, also a double, consists of one bright star and one dark star. The dark star, a stellar mass that either has ceased, or not yet begun to shine, is detected by virtue of its gravitational effect on its bright companion, which is caused to revolve. Alcor, too, is known to be a double star.

Thus what seems at first glance to be a single star turns out to be a system of six suns moving in a complicated manner, radiating some seventy times as much light and heat as our own sun, and traveling through the galaxy at approximately 60 miles per second. All but two of the principal stars of the Big Dipper are moving with them in the same direction, at the same speed. So also is Sirius, our brightest star, 8.8 light-years distant, and many others, including Beta Aurigae, the bright star near Capella, 135 light-years from the solar system—a splendid parade through space, one group within which we lie but in whose common motion we do not participate.

THE BRILLIANT WINTER SKY

Everyone has noticed the richness of the winter sky. In a great horseshoe one finds many of the most familiar objects and constellations, including the Pleiades; the Great Nebula of Orion; the famous twins, Pollux and Castor; Sirius, our brightest star; and, including Pollux and Sirius, seven of the fifteen first-magnitude stars that are visible from latitude 40 degrees north.

The Horseshoe. Imagine yourself facing due east in the early evening late in December. You are facing the horseshoe. Its prongs stretch up towards the zenith, the curved part grazes the horizon. Beginning at the top at our right, swinging down to the horizon, then across to the left and up the other prong, we find: the *Pleiades;* the *Hyades; Aldebaran; Betelgeuse* and *Rigel; Sirius; Procyon; Pollux; Castor; Capella.*

The curve joining the two prongs is formed by Sirius at the right and Procyon at the left, both only a short distance above the horizon. Later on in the year the whole group will be higher, and in the late spring will be setting in the evening; but if the observer will memorize the names in the order given he will never have any difficulty in recognizing this richest of all heavenly groups. The stars maintain the same relative positions as the whole panorama wheels through the sky. It is useful to memorize the names in the fall and watch the horseshoe slowly rise, prongs first, bringing Pleiades and Capella into view in the early evening in October.

Pleiades and Hyades. These clusters of faint stars are, with the first-magnitude star Aldebaran, the most beautiful objects in the constellation Taurus, the Bull. Aldebaran is the animal's red eye. In a pair of low-powered binoculars the Pleiades (the Seven Sisters of antiquity) reveal a question-mark, perfect except for a careless misplacing of the dot a little to one side at the foot. All

FIGURE 89. Great Nebula in Orion. (Photographed at Mount Wilson Observatory.)

should put the glasses on this beautiful sight. The Hyades are a V-shaped cluster lying on its side and terminating in Aldebaran. The whole region is full of optical doubles that are easily separated with the field glasses.

Orion. The Great Hunter's belt of three second-magnitude stars crosses at right angles the line joining Rigel and Betelgeuse. These two first-magnitude stars give Orion rather more than his fair share of brilliance. Rigel is the one farther south — a star so much hotter than our sun (28,000 degrees Fahrenheit against 10,000, approximately) that it appears not white-hot, but bluish-white. Betelgeuse is the red star, not as hot as our sun but larger than the orbit in which the earth revolves around the sun.

One notes also the sword thrust through Orion's belt at a rakish angle, and, in the region of the sword, the *Great Nebula* of Orion, which well repays study in the literature and observation with the telescope. Several multiple stars are embedded in the nebula. When one recalls that Betelgeuse, large as it is, remains a point of light in the telescope, he can infer from the easily visible extension of the nebula how large it must actually be to show size at its great distance. Bellatrix, a second-magnitude star, is diagonally across the belt from the nebula.

CASTOR — AN EASY DOUBLE STAR

Castor is the favorite double star of many observers. Castor is one of the famous twins, the Gemini, and misses by only a fraction of a magnitude the privilege of joining Pollux among the first-magnitude stars. The telescope reveals Castor as a beautiful double star whose components are of comparable brightness. One component has a luminosity 24 times that of the sun, the other 11. Their distance from us is 42 light-years. With the spectroscope

astronomers have found that each of the components is itself a double star. A faint companion of this quadruple system, 73 seconds of arc away, is also a binary.

THE MILKY WAY

On a clear, dark, moonless night, far from any artificial lights, one should inspect the Milky Way, first with the naked eye, then with the lowest-powered eyepiece that is provided with the telescope. Turn the telescope from one part of the Milky Way to another, and observe how its hazy light is resolved into thousands of individual stars. The solar system lies somewhat off center in a discus-shaped galaxy of stars, and looking out through the galaxy the long way, towards the rim of the discus, we notice the massed effect of millions of stars too faint to be detected individually with the naked eye.

THE SIZES OF STARS

The sizes of stars are found to be such that we may consider our sun an average star. Many are smaller, many larger. Many are hotter, many cooler. Only the largest have been directly measured. Of these we select the five that are best known, and give their diameters below.

Star	Diameter in Miles	Diameter Compared with Sun	Volume Compared with Sun
Antares	390,000,000	450	90,000,000
Aldebaran	330,000,000	380	55,000,000
Mira	280,000,000	320	34,000,000
Betelgeuse	260,000,000	300	27,000,000
Arcturus	230,000,000	270	20,000,000
The Sun	864,000	1	1

Mars' orbit could go inside Antares as easily as the moon's orbit could go inside the body of our sun. But let us not infer that all stars reach these gigantic proportions. Some have been found to be very small. The table includes five of the largest known.

ALGOL AND MIRA — TWO VARIABLE STARS

The heavens contain thousands of stars whose brightness waxes and wanes. These are called variables. Several stars mentioned in this brief outline, for example Betelgeuse and Polaris, present changes of brightness; but to represent the variables we select Algol and Mira, two of the most interesting objects which the amateur astronomer can study.

Algol (the Demon). Late in December the constellation Perseus is high in the heavens in the early evening, between Taurus and Cassiopeia. Despite its lack of first-magnitude stars, Perseus is beautiful to the unaided eye and through the binoculars presents a starfield of surpassing richness, full of interesting optical doubles. A straight line from the Pleiades to the middle of the "W" of Cassiopeia passes through Perseus very close to Algol. The three brightest stars of Perseus lie nearly in a straight line. The brightest of these marks the north end of the line: Algol, the second brightest, comes next; then, very close to Algol, we find the third, ending the line.

Algol's changes of brightness are so conspicuous that its variability has been recognized for centuries. It is what is known as an eclipsing binary, consisting of one bright and one dark star which revolve around their common center of gravity in 2 days 21 hours. The dark star may be either too young to shine or well past its prime, we cannot surely state which. When the dark star gets in the way Algol's brightness drops rather quickly to one-

third of its normal value—from the magnitude of 2.2 to 3.4—but within four hours the dark companion moves away from our line of sight and Algol presents again its usual brightness.

A few interested members might set themselves the project of finding when Algol changes brightness. To succeed with the eye alone, without referring to the literature, one might at the worst need to look every evening for some 21 to 24 days. The most probable time required would be half that, and of course fortune might smile the first night. Once the hour of brightening or dimming had been discovered, predictions based on the period of 2 days 21 hours could be made for the benefit of the whole group.

Mira (*the Wonder-star*). At the same time of the year, a December evening, an apparently barren constellation, Cetus, the Whale, sprawls across the southwestern sky, stretching from the meridian far to the southwest. A little to the east of the middle of this constellation, at a point to be found with the aid of star maps, lies an object which richly merits its name. *Stella mira,* the astonishing star; Mira, for short! Normally Mira is of the 8th to 10th magnitude, 6 to 39 times fainter than the faintest naked-eye stars; but for about one month of every eleven it becomes visible to the unaided eye and sometimes is a brilliant object of magnitude 1.5. Its usual brightness at a maximum is the second magnitude, a conspicuous object in that poverty-stricken part of the sky; though in some years it becomes no brighter than magnitude 5.6. The usual increase of brightness from a minimum to a maximum ranges from a few hundred to several thousandfold.

The cause of this remarkable behavior is not known. Fabricius noticed it more than three centuries ago, in 1596. Mira's light requires about a century and a half to reach us; its diameter averages approximately 320 times that of our sun but is not constant. This giant red star pulsates, expanding and contracting so much that at its largest it is about 60,000,000 miles thicker through the

center than when smallest. What would happen to us if our sun expanded even a few million miles? Following Mira's baffling performance with binoculars and small telescopes affords many amateurs an interesting pastime; but the difficulty of locating a faint object without a permanent equatorial mounting for the telescope should not be underestimated.

EIGHT ANNUAL METEORIC SHOWERS

When dealing with atmospheric effects in Chapter 3 we considered the nature of the sporadic daily bombardment of meteors, or shooting stars, and referred to the meteoric showers that occur at certain dates, bringing more than the usual number of meteors to light up the sky. Swarms of meteors, the remains of disintegrated comets, circulate around the sun in elongated orbits, some of which cross the earth's orbit. Year after year, when the earth reaches such a point in its orbit, it encounters meteors with unusual frequency for a night or two.

The path along which the earth encounters the moving swarm necessarily points to one constellation or another, and since the luminous streaks of the meteors are the results of the motion, they seem to radiate from that constellation. For this reason showers are named for constellations. Eight of the most promising are listed below. Since the constellation must be above the horizon if the meteor-counter is to have an opportunity to try his luck, the list includes the approximate hours of rising of the constellations.

Orionids — Oct. 19–20 — Orion rising south of east about 11 P.M.

Leonids — Nov. 14 — Leo (the Sickle) rising in the east about 1 A.M.

Andromedes — Nov. 20–27 — Andromeda near zenith about 8 P.M.

Geminids — Dec. 10–11 — Gemini rising north of east about 7 P.M.

Lyrids — April 20 — Lyra rising in northeast about 8:30 P.M.

Aquarids I — May 5–7 — Aquarius rising in southeast about 1 A.M.

Aquarids II — July 27–29 — Aquarius rising about 7 P.M.

Perseids — Aug. 11–12 — Perseus rising in northeast about 8:30 P.M.

Since astronomers have met with only partial success thus far in predicting the years in which a given shower will be especially noteworthy, the observer should be prepared for something less spectacular than those few historic showers which have turned the sky into an umbrella of shining streaks.

COMETS

Since comets are rarely objects of great interest to the amateur observer, at least to one who possesses very modest telescopic equipment, we dismiss them rather briefly here. As a class of heavenly bodies, however, they will repay study in one of the references cited at the end of Unit 1. Most comets, if not all, are members of the solar system. They shine partly by reflected sunlight, partly by light which they emit themselves. The tail is gaseous; the head, considerably denser, a loose aggregation of relatively small bodies. Many tailless comets have been seen, and some have been observed to lose their tails and later emit new ones from the head. About one-fourth of the recorded comets are known to revolve around the sun in elongated orbits, and most of the others are believed to do likewise. A few may possibly be transient visitors to the solar system. An average of three or four

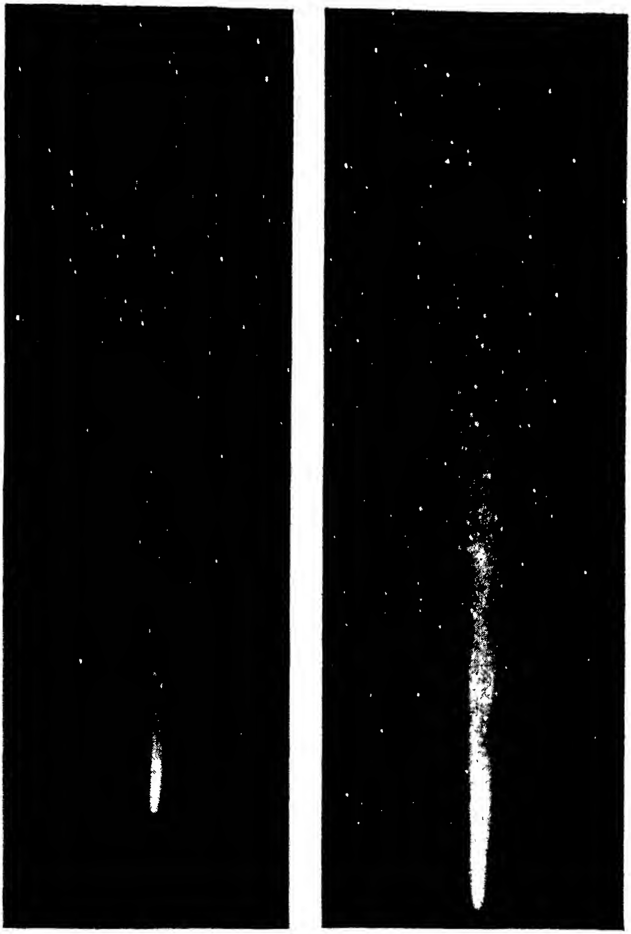


FIGURE 90. Halley's Comet, May 12 and 15, 1910, as photographed at Honolulu. (Courtesy Mount Wilson Observatory.)

new comets are discovered annually; others, long known, return. Most comets are faint telescopic objects. Occasionally, one bright enough to be seen in broad daylight appears. Halley's comet is one of the best known of these. At least since 240 B.C. this magnificent object has been returning at intervals averaging 77 years long. At present, about 75 years elapses between two successive returns of Halley's comet. Its last appearance was in 1910; its next is expected in 1985. It is now beyond Neptune.

DISTINGUISHING PLANETS FROM STARS

As the planets revolve around the sun we see them projected against one constellation after another. One who knows the constellations immediately recognizes the bright interloper as a planet, not a star; but in the early stages of the study confusion sometimes results. One can often distinguish a planet from a star by the planet's brilliance and steadier light. Planets are not immune to twinkling; but because of their nearness they appear to cover so much more space in the sky than a star does that we receive light as if from a disk instead of a point. In other words, the beams of light from planets appear broader than those from stars, and the broader the beam, the less chance there is that a localized fluctuation of air in its path will divert the whole beam and produce an apparent twinkling of the source.

The Zodiac. There is a better method. In Chapter 4 we drew an important conclusion from the fact that the planes of the orbits of the nine planets, while not coinciding, are inclined to one another at angles so small that there is only one fairly narrow belt in the heavens, called the zodiac, in which planets ever appear. This belt traverses twelve constellations, as follows: Aries, Taurus, Gemini, Cancer, Leo, Virgo, Libra, Scorpius, Sagittarius, Capri-

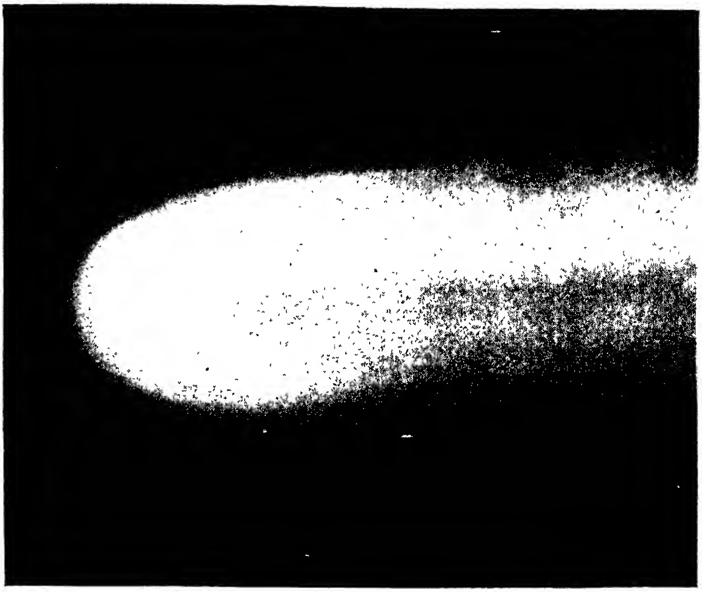


FIGURE 91. Head of Halley's Comet, May 10, 1910. (Photographed at Mount Wilson Observatory.)

FIGURE 92. Photographs of Mars made a month apart. (Mount Wilson Observatory.)

cornus, Aquarius, and Pisces. Four of these constellations are very conspicuous. *Taurus* contains the Pleiades and Aldebaran. *Gemini* is marked by the twins, Pollux and Castor. *Leo* is the Sickle, with Regulus, a first-magnitude star, marking the end of the handle. And the long curving line of *Scorpius* is punctuated by the red giant, Antares.

Even if the other constellations of the zodiac may not now be familiar to the observer, their names have, so to speak, a *negative* value. If the name of a certain constellation does not appear among the twelve, the reader may be sure that a bright object in it is *not* a planet.

MERCURY AND VENUS

To observers who depend on the naked eye or on telescopes of moderate size, Mercury and Venus are interesting for two principal reasons.

Morning and Evening Stars. Because of their nearness to the sun, Mercury and Venus must always set either shortly before, or shortly after the sun, and are correspondingly close to the sun at daybreak. Thus they never appear very high in the sky. When poets refer to the morning or evening star they mean either Mercury or Venus, probably the latter. Mercury is so close to the sun that many persons pass a lifetime without ever seeing it. Venus, however, remains above the horizon for several hours after sunset when most favorably placed, shining with a brilliance five magnitudes brighter than a typical first-magnitude star and thus dominating the sky with a beauty which fully justifies the glowing terms of the poets.

The ancient Greeks called Mercury by its present name when it appeared as an evening star, but Apollo when a morning star. For Venus also they had two names — Hesperus when the evening

star and Phosphorus in the morning. What they considered to be four different bodies we recognize as two.

Phases. The second great interest of these two bodies for the average observer is their phases. Since their orbits lie within the earth's they occasionally assume the crescent phase for the same reason that the moon does. There is no more intriguing sight in the heavens than Venus shining like a new moon in the telescope while beside it the observer sees with his unaided eye the slender crescent of the real new moon. Of course Venus must lie nearly between the earth and the sun to show this interesting effect, and it must be on a certain side of the line joining the earth to the sun if it is to appear in the evening sky rather than in the morning.

Physical Characteristics. By studying Table 1 the reader will be able to deduce a number of interesting consequences from the data for Mercury and Venus. Mercury is the smallest of the planets, the nearest to the sun, it moves more swiftly in its orbit than any other, and completes a revolution about the sun in the shortest time. It receives six times as much light and heat per square mile as the earth does, so close is it to the power-plant of the solar system; and hence must be exceedingly hot on the one face which, as seems probable, it perpetually turns to the sun.

Venus is nearly the twin of the earth for size, and comes nearer to us (26,000,000 miles) than any other *planet.* Yet we know surprisingly little about its surface conditions. When it is closest its sunlit face is turned away from the earth. Its atmosphere, always cloudy, so thoroughly obscures the solid surface that we do not yet know how fast it spins on its axis, though its negligible departure from true sphericity indicates that the rotation must be very slow. Hence, the "day" is long and the daylight temperatures high.

What gases there may be beneath its clouds we can only infer

from a partial analysis of its upper atmosphere. Above the clouds there is, if any, less than a tenth of one percent as much oxygen as there is above our own clouds. To judge by the absence of oxygen, not even vegetable life has developed on Venus. To those interested in learning of new neighbors this is disappointing. Surface gravity is 0.88 times the earth's, ample to retain a suitable atmosphere; and the supply of heat and light, while greater than on earth, is not so great as to preclude life in certain intermediate zones. But an adequate supply of oxygen, if present, would be readily detectible above the clouds as a result of diffusion. Apparently, life does not exist there.

MARS

Mars is very favorably situated for observation when nearest the earth; for then we are between Mars and the sun, and the sunlit half of Mars faces the night side of the earth. When Mars is in opposition, as this position is described, it is not only close but visible throughout the night. Since its orbit lies outside the earth's, Mars can never come between the earth and the sun and thus never shows the crescent phase. At an average opposition Mars is 48,600,000 miles from the earth, though the distance may, on rare occasions, be as small as 34,600,000 miles; and when on the other side of the sun Mars is very remote (234,400,000 miles), for then we must look across the earth's whole orbit and beyond.

Appearance. The brightness of Mars changes greatly as a result of the variation of distance. At its dimmest it is not as bright as Castor; and when brightest it has a magnitude of —2.8, more brilliant than any star and surpassed only by Venus, the moon, and the sun. The observer should not be misled by these facts: Mars is not as satisfactory an object in telescopes of moderate size as many anticipate. There has been so much talk about Mars that the in-

experienced observer sometimes seems subconsciously to expect not only canals but harbors crowded with ships; whereas now, after the half-century of unparalleled concentration on Mars that followed Schiaparelli's announcement of the discovery of *canali,* photographic proof of their existence is still lacking and astronomers working with the most powerful observatory equipment are divided in their opinions.

What a telescope of moderate size may be expected to show is a beautiful ruddy disk bearing a few hazy marks and departing from perfect roundness about half again as much as the earth does. The observer thus finds proof that Mars is an object within our own solar system; for all the stars, even the brightest, largest, and nearest, remain mere points of light in the greatest telescopes. The permanent features show that a solid surface is being viewed; and if a glimpse of a white polar cap can be secured, as is possible under the most favorable conditions of time, position, and seeing, one reason for our conclusions regarding Mars' atmosphere and seasonal changes will be apparent.

A good comprehension of the distance of Mars should result if the observer reflects that a telescope on Mars similar to the one he is using would reveal the earth as a small round disk not quite twice as wide across the center as Mars appears to him. Of course if the observations were made simultaneously, at a time when the full bright half of Mars faced the earth's night side, the earth would present the crescent phase to the hypothetical Martian observer.

Satellites. The moons of Mars, two of the most interesting objects in the solar system, have been described in Chapter 3.

Principal Characteristics. A study of Table 1 brings to light a number of interesting facts about Mars. It is a small planet, nearer in size to Mercury than to the earth. It revolves more slowly than the earth: each season on Mars lasts about five and a half months.

The inclination of its equator to the plane of its orbit is nearly the same as the earth's, slightly greater; hence the seasons, except for lasting nearly twice as long and progressing on a lower level of temperature, are closely comparable to ours. Day and night, also, are nearly the same length as ours: Mars spins on its axis in 24 hours 37 minutes 22.58 seconds. Long observation of its permanent surface features makes this great precision of statement possible.

A 100-pound object weighs 38 pounds on Mars. This value of the surface gravity, though small, is more than twice that at the moon's surface and enables Mars to retain all atmospheric molecules which do not attain outward velocities as high as 3.13 miles per second. It cannot hold the lighter gases, hydrogen and helium, whose molecules move the fastest; but it can retain oxygen, nitrogen, carbon dioxide and, just barely, water vapor.

Atmosphere. Of course the atmosphere which that relatively feeble surface gravity holds is much rarer than ours; but there is abundant proof that Mars does possess an atmosphere. Clouds, fog, and haze appear occasionally; there is twilight on Mars; the appearance and disappearance of the white polar caps point to precipitation from an atmosphere and subsequent melting and evaporation. The atmospheric pressure at the surface is not surely known. It is estimated at about 1/4 to 1/6 of the normal value at sea level on earth, or 1/2 to 1/3 of the pressure at man's highest permanent dwelling place in the Andes.

Until recently it was believed, on the basis of spectroscopic measurements made at the Lowell and Mount Wilson observatories, that there was 5 percent as much water vapor above Mars' surface, in proportion to area, as there is above the earth's, and 15 percent as much oxygen; but very recent results suggest a smaller amount of oxygen, possibly as little as one percent.

Temperature. Because of its greater distance from the sun Mars receives 43 percent as much heat per square mile as does the earth, a value so low that if the reflecting and absorbing characteristics of the two planets were similar the *average* surface temperature of Mars would be 39 degrees below zero Fahrenheit, 99 degrees below the earth's average.

But Mars' thin atmosphere reflects back into space a smaller fraction of the incident radiation and so permits more heat to reach the solid surface than the first figure suggests. There is no doubt that Mars is relatively cold; but a low average temperature does not preclude livable conditions in the more favored regions. Measurements with sensitive electrical radiation thermocouples show that the equatorial temperature rises to about 70 or 80 degrees above zero Fahrenheit at noon and falls every night below the freezing point of water.

Seasonal Changes. A recent discovery that the amount of water vapor above the polar caps increases when the caps are diminishing seems to confirm our natural conclusion that they are composed of snow which melts in the summer. The caps must be very thin, for a number of reasons. The atmosphere is too rare to provide a very dense precipitation; the caps sometimes form overnight; and the total available amount of heat, calculated with due regard for losses by reflection, could melt and vaporize an ice-layer of an average thickness not exceeding a few inches, yet the caps disappear either completely or nearly so every winter.

With powerful telescopes it is interesting to watch one polar cap forming while the other is disappearing. On Mars, as here, the approach of winter in one hemisphere coincides with the coming of summer in the other. In some summers the southern cap vanishes completely, the northern cap never; yet the southern cap is usually larger than the northern, 3700 miles across against 3100 miles. This

shows the greater severity of both winter and summer in the southern hemisphere. In this respect, too, Mars resembles the earth. In consequence of the ellipticity of the earth's orbit, the earth approaches 3 percent closer to the sun in December than in June, thereby increasing in the southern hemisphere (and decreasing in the northern) the severity of the seasonal changes, which of course are primarily due to the varying duration of daylight and directness of the sun's rays.

Other seasonal changes of unquestionable reality accompany the regular appearance and disappearance of the polar caps. With the polariscope W. H. Pickering established the existence of a liquid surface — a polar sea — at the foot of a shrinking cap. Most of the planet's surface remains arid, an orange-colored desert; but in certain regions a progressive darkening recurs summer after summer, apparently the result of vegetation springing up in the path of water that is formed by the melting of the snow. Even if no direct evidence of vegetation were presented we should suspect its existence because of the traces of oxygen in Mars' atmosphere. This element, as we have seen, is so active chemically that the supply must be replenished, a function performed by vegetable life.

But the direct evidence is convincing. The supposedly watered areas turn from dark green to brown to dark green again — spring, autumn, spring. Certain equatorial localities apparently witness two revivals of vegetation in one Martian year, as if they benefited by the melting of both polar caps, one after the other.

Is There Intelligent Life on Mars? The long debate on this question hinges on a question of evidence. The reality or unreality of certain markings must be decided — but first let us consider what kind of evidence would be acceptable proof of the existence of intelligent beings beyond the earth.

A moment's reflection will show that both design and a certain arbitrariness must be established. Nature herself exhibits so much of design that the proof would be incomplete without a capricious element involving choice or will. Old Faithful Geyser spouts with remarkable regularity, and it is conceivable that natural causes might even produce discharges which followed one another at intervals like those of a Morse code signal, say two longs and a short. A distant observer might conclude, erroneously, that the apparent design or timing of the discharges showed human agency. But if water were observed spouting both capriciously and with the quality of design, changing, say, from one Morse signal to another and still another, the inference of artificiality would be inescapable. Changes of such a nature, on so grand a scale as to be detectable at planetary distances, would furnish the most satisfying evidence.

But both design and will can reveal themselves in another manner. Together they can accomplish results which natural processes, if left to themselves, would not produce. If we see an inanimate object continuing to fly steadily through the air directly against the wind, we know it has a propeller of some sort. If we find water running continuously uphill to a height above its source, we suspect a pump somewhere in the background. In 1915 an eminent American astronomer, after twenty years of investigation with a splendid telescope, reiterated his belief that water is flowing uphill on Mars.

Percival Lowell, founder and director of the famous observatory at Flagstaff, Arizona, is the best known of all the proponents of the canal-theory of Mars; but there has been no lack of astronomers whose findings and conclusions agreed, in whole or in part, with his. Schiaparelli, who in 1877 discovered the *canali* (literally, "channels"); Perrotin, Thollon, Flammarian, Douglas, W. H.

Pickering — these have testified to the existence of a complicated geometrical pattern of fine dark lines which showed seasonal changes as if vegetation were springing up along them under the revivifying influence of water that flowed through them as the polar caps melted, and all were well qualified by virtue of training, excellence of instrumental equipment, and acuity of vision established by undisputed discoveries in other astronomical fields.

Lowell, who developed the picture of engineering on Mars so thoroughly and ingeniously that it has a permanent place in the history of thought, named approximately 400 canals, fifty of them accurately paralleled by others to form double waterways; and 200 oases situated at the junctions of canal systems. He gave the widths of the strips irrigated by the canals as 15 to 20 miles; the separation of double canals 100 to 200 miles; the breadth of the oases or central collecting basins 75 to 100 miles; and he reported that a few individual canals traversed both hemispheres and conducted water towards the equator from whichever polar cap was melting at the time.

Even if the geometrical pattern of this intricate network be insufficient to establish the existence of high intelligence on Mars, argued Lowell, no natural waterways could be downhill all the way for the thousands of miles from pole to equator. And certainly no natural waterway could be downhill in both directions at once! Yet in certain instances one and the same canal carries water north of the equator when the southern polar cap is melting, and south of the equator when the northern cap melts. Not only has a race of vision conquered the aridity of its planet, said Lowell, but that race at this moment is operating on a gigantic scale a beautifully engineered system of locks and pumps. They make water go uphill on Mars, he said, when the season demands.

Against this inspiring conception we must set the testimony of

equally competent observers. One of the greatest American astronomers, Edward Emerson Barnard, long-time director of Yerkes Observatory, discoverer of the fifth satellite of Jupiter, of Barnard's star and numerous dark nebulae — an observer so gifted that even when a youth, working with a telescope inferior, for example, to the 5⅜-inch instrument which the student telescope team of Florida State College for Women regularly wheels around on the campus, he discovered a new comet — Barnard never succeeded in seeing any canals on Mars. Neither did Antoniadi, who worked with the best telescope in Europe. Two European astronomers, taking turns one night at the eyepiece of a powerful instrument, gave precisely opposite reports on the reality of a supposed double canal, and a little later heard that an independent observer several hundred miles away had seen it double that same night.

Vegetable life seems to exist on Mars, but the case for animal life is very dubious. Probably the famous experiment of Evans and Maunder with the English schoolboys gives the answer to the question of the canals. They placed numerous barely visible dots at random on pictures of Mars and found that most of the boys thought they saw lines. True, Flammarian in France found boys drawing no lines at all in a similar experiment, and all observers find some markings on Mars; but informed opinion today holds, though not unanimously, that the canals are optical illusions.

One may wonder why telescopic photography, which reveals so many stars that the eye at the same telescope cannot see, has not disposed of this question. In studying minute details on an extended surface the eye takes advantage of instants of good seeing when the air steadies or clears for a moment, and thus detects markings which would be obliterated during the long exposures required in telescopic photography.

To the proponents of the canal theory we cannot say yes; we say probably, but not certainly, no. Conceivably the new 200-inch telescope now under construction in California may revive the discussion. Probably it will bury in history our hopes of intelligent life on our neighbor-planet — though not, one may be permitted to believe, without a few wreaths at the funeral and a monument dedicated jointly to Lowell and to a race that might so easily have been.

JUPITER

Jupiter is a planet which should by all means be included in the program of the observer who is studying the heavens telescopically for the first time. With an instrument of very moderate size one can readily follow the rapid motions of the four brightest of Jupiter's moons, which have been briefly discussed in Chapter 2 in connection with Galileo's great work. That section should be reviewed in preparation for the occasion.

The oblateness of the planet and the equatorial belts of dense clouds are easily detected; and if when noting the large disk one remembers that Jupiter is never closer than 367,000,000 miles and at its farthest is nearly 600,000,000 miles away, the great size of this giant among planets will be apparent.

Size. The diameter of Jupiter is nearly 11 times that of the earth, and its volume so great that it fills 1315 times as much space. The fact that Jupiter shows a disk at all establishes its identity as a member of our system. How near this is relative to the stars may be judged by comparing Jupiter's telescopic appearance with that of Antares, the largest measured star — a red-hot giant whose diameter is 4500 times that of Jupiter and which shines with the luminous intensity of 3400 suns, yet remains a point of light in the largest telescopes.

Brightness. Despite Jupiter's relatively great distance, its size is such that it reflects a great deal of sunlight and is one of the most conspicuous objects whenever it appears in the night sky. While never quite as bright as Mars' brightest, Jupiter does not present the great changes of brilliance which characterize Mars and so usually surpasses it. Jupiter's brightness changes for the same reasons that Mars' does; but Jupiter is so much farther that to add or subtract the distance across the earth's orbit is not so important relatively. In stellar magnitudes, Jupiter's brightness varies from —1.4 to —2.5.

Surface Characteristics. Jupiter is not only the largest of the planets; it spins the fastest on its axis. Therefore a great centrifugal force exists, which of course is greatest at the equator. The very noticeable equatorial bulge gives evidence of this. The striking arrangement of clouds in belts parallel to the equator is doubtless also due in part to the high rotational speed. A 100-pound object would weigh 284 pounds at one of Jupiter's poles but only 244 at the equator.

Not only does Jupiter spin rapidly — different parts of it rotate at different rates. A point on the equator gets around in 9 hours 50 minutes (a short time from sunrise to sunrise) and travels at a speed of 28,000 miles per hour. Compare that with our own modest equatorial speed of 1041 miles per hour. At higher latitudes the rotation period is 5 minutes longer. The broad equatorial belt drifts past the regions on either side at a relative speed approaching 200 miles per hour. This is not an atmospheric hurricane that we are observing; for conspicuous features have been followed through many complete rotations while shifting past each other at such speeds. Imagine conditions such that one could not state the distance from Atlanta to Miami without consulting both a watch and a calendar. One might be tempted to wait until Miami

came due south and then quickly fly over. But of course that is nonsense. Jupiter obviously cannot have a solid surface. There must be an outer shell of gas too deep and too dense to be entirely an atmosphere, and the central core must be very concentrated.

Finally, Jupiter is very cold. Radiometric measurements reveal a surface temperature 220 degrees below zero Fahrenheit.

Jupiter's Satellites. The short discussion in Chapter 2 showed what to expect when studying Jupiter's rich endowment of moons. The five faintest are so small that they are beyond the light-grasp of all but the greatest telescopes. The four large moons are easily seen, and to these we address ourselves.

At the time of observation the chart which appears regularly in *The Monthly Evening Sky Map* should be consulted for the positions and directions of motion of the moons, also for possible eclipses behind, or transits across, Jupiter's disk. These four moons have names but are usually identified by numbers — 1, 2, 3, 4 — in order of increasing distance from the planet. When Jupiter is in opposition (in view all night) their brightnesses are, in order, approximately 5.5, 5.7, 5.1, 6.3 magnitudes. We see that the first three would be visible to the naked eye if they stood alone in a dark part of the sky where they did not need to compete with an object of Jupiter's brilliance.

In the great observatories the moons can be identified by their sizes and surface markings, but with lesser equipment one must rely on a chart or follow their changes of position for a while. If we were able to view their orbits face-on, their distances would reveal their identities at a glance. Looking *across* their orbits, as we do, we see the moons apparently moving back and forth in a line, and the one seen nearest the planet is not necessarily closest to it.

The periods in order, beginning with No. 1, are 1.77, 3.55, 7.15,

16.69 days. Hence the moons move very rapidly. Number 1, for instance, requires less than two days to complete a revolution or, as seen in the telescope, to move from its extreme distance on one side of Jupiter to the extreme on the other, and back again. When two moons are apparently passing each other, or when one is about to disappear behind or before Jupiter, the movement becomes apparent in a few minutes.

All these four satellites are comparable in size to our own moon. Their diameters, in order, are 2320, 1960, 3210, 3220 miles. All but one are larger than our moon, and the two largest exceed the planet Mercury in size. Their distances from the *surface* of Jupiter, in order, are 218,400 — 373,200 — 620,800 — 1,125,000 miles. By comparing these values with the distance of the whole system from us at an average opposition (390,000,000 miles) we find that the four moons are 1790, 1040, 627, and 346 times as close to Jupiter's surface, respectively, as to us. To find how many times brighter they would appear from Jupiter's surface than from the earth we must square these numbers, for the illumination falls off as the square of the distance.

Squaring them, then, and then calculating how many times 2.512 must be multiplied by itself to give the results, we learn how many magnitudes brighter the moons would appear if viewed from Jupiter's surface. The results are very interesting. These four moons, when full, would present brightnesses of about —10.9, —9.4, —8.9, and —6.4 magnitudes, respectively, and would accordingly be brilliant objects in the sky. Remember that minus magnitudes are used to designate the brilliance of objects that are too bright for the usual positive scale. Compare those results with —12.55, the brightness of our own full moon, and one finds that the four, though surpassed by ours, would be objects of great beauty.

Satellite No. 5, the next largest after these four which we can study outside of observatories, is only about 100 miles in diameter, but revolves so close to Jupiter's surface (69,000 miles) that it would be conspicuous even though tiny if viewed from there. Its maximum brilliance would be about —5.8 magnitudes. Moon No. 6 would be nearly at the limit of naked-eye visibility; and to see his own three faintest moons the hypothetical observer on Jupiter would require a telescope.

Jupiter's coldness, its dense atmosphere, and the difficulty of finding something solid to stand on, all render our comparisons, in one sense of the word, highly academic; but by building a picture of the moons as viewed from a different locality we understand better both them and our own situation. When, with our good modern equipment, we follow these moons through their paths around Jupiter, we are treading in the footsteps of Galileo — and we are also gaining for ourselves a true and unforgettable conception of the reality of the Copernican system of orbital motion.

SATURN

To see Saturn through the telescope is part of a liberal education. Certainly everyone studying the nature of our physical environment should view it. Its beautiful rings render it unique among the planets. If the queen of the heavens is to be chosen, the judges with their eyes at the telescopes will hesitate only between Saturn and the moon. The same quick intake of breath marks one's first glimpse of each.

Distance, Size, Density. Saturn is the farthest of the planets that needed no discoverer. It is never closer to the earth than 745,000,000 miles, and at its farthest is slightly more than a billion miles away. To form a true estimate of Saturn's great size the observer

at the telescope should bear in mind that he is looking at something which is, on the average, 3700 times as far from him as the moon. Saturn is the second largest of the planets, its diameter nine times that of the earth. Its volume is 734 times the earth's but its mass only 94.9 times as great; hence we see that Saturn is composed of light materials. The mean density is 71.5 percent of that of water. Saturn is the only planet that would float in water if it could remain unchanged during a launching on so grand a scale.

Revolution, Seasons, Temperature. Saturn takes 29.5 years to revolve around the sun. Thus, as seen from the earth, Saturn moves very leisurely from one constellation of the zodiac to another, remaining in one constellation more than two years. Seasons on this cold gaseous body last more than seven years each, and in one sense of the word are more marked than those on earth; but their influence on the gaseous peripheral layers is probably unimportant because of the low average temperature (about 240 degrees F. below zero) of the surface.

Rotation, Shape, Surface. Saturn spins rapidly on its axis. Its "day" — from sunrise to sunrise — averages slightly more than ten hours long. Different parts of the surface rotate at different rates. In this respect, as also by virtue of its great size and rapid spinning, Saturn resembles Jupiter. The equatorial region has been observed to complete a rotation 24 minutes sooner than a point at latitude 36 degrees north. This confirms the evidence of the low density in pointing to a gaseous outer shell. Most of Saturn's mass is evidently concentrated in a core at the center. Through the telescope one can hardly fail to notice the extreme oblateness, or departure from sphericity, of the planet. As a result of its rapid spin and its largely gaseous nature, Saturn bulges more than any other planet.

Nature of Saturn's Rings. The silvery bands of light completely

encircling Saturn are, once well seen, an unforgettable sight. To the eye at the telescope the brighter rings appear solid; yet the spectroscope proves that they are composed of dense swarms of meteors revolving around Saturn in lieu of an extra moon or two.

FIGURE 93. The Rings of Saturn. They passed through the edgewise aspect in the winter of 1936–37, and will attain their widest opening, as viewed from the Earth, in December 1943. (Photographed by E. C. Slipher, Lowell Observatory.)

With the spectroscope, as we noticed in Chapter 18, one can not only discover whether a source of light is approaching us or receding, but can also measure the relative velocity. In 1895 J. E. Keeler demonstrated that the inner part of each of Saturn's rings is traveling at a higher speed than the outer portions. Hence the rings cannot be solid sheets of matter; for in that case the inner parts, like points near the hub of a turning wheel, would be moving more slowly than those at the outer rim. But if the rings consist of innumerable independent particles, each moving in its own orbit about Saturn at the speed which produces the necessary balance between centrifugal force and the gravitational attraction of the planet, the inner particles must be moving the fastest. Notice, in Table 1, how the planetary speeds decrease as the distance from the sun increases. The same laws apply to the meteors which compose Saturn's rings.

The innermost particles are found to be moving at about 15

miles per second, the outermost 11. At these speeds they complete their orbits around Saturn in about 5 hours and 13.7 hours, respectively. No telescope can detect the meteors individually as they shine in the sunlight; but through the innermost ring, called the crape ring on account of its dimness, the brighter of Saturn's moons can occasionally be seen. Thus the spectroscopic proof of discontinuous structure of the rings is confirmed.

Dimensions of the Rings. The rings are so thin that they shine in the sky like a luminous enlargement of Saturn's equator. Standing on the planet's equator and looking towards the zenith, one would see the rings exactly edge-on, a very narrow band of light not more than some 10 to 30 miles wide and arching across the sky from horizon to horizon. Traveling upwards, as we did when surveying our atmosphere, one would pass through 7000 miles while en route to the innermost edge of the dim crape ring. Then, in order: 11,000 miles through the crape ring; 17,000 miles through the principal bright ring; 2000 miles through an empty dark space known as Cassini's division; and finally, 11,000 miles through the outermost ring.

It is easy to picture how magnificent a spectacle the rings would present to an observer situated a few degrees north or south of Saturn's equator. But so close are the rings to Saturn, in proportion to its diameter, that our hypothetical observer must not travel farther from the equator than Nome, Alaska, is here, by latitude measure, or he will find that the rings are invisible, completely hidden behind the round surface of the planet. From a latitude corresponding to Seattle's the inner edge of the principal bright ring would be level with the observer's horizon and so would appear to form a perfectly fitting collar of light.

Phases of the Rings. The rings are usually seen obliquely. Saturn has been likened to an orange resting in a shallow soup

plate and viewed from an angle not more than 28 degrees above the top of the dinner table. The rings are never seen face-on, never more than 28 degrees from edge-on; and once every 14¾ years they appear to us edge-on and so are nearly invisible because of their extreme thinness. The years 1936–37 and 1950–51 will find the rings in their worst phases, from the observer's point of view, though actually disappointing for only a few months during each of those periods. In 1943–44 the rings will present their most beautiful aspect.

Saturn's Satellites. Saturn, like Jupiter, has nine moons, of which five are within fairly easy reach of a four- or five-inch telescope. Usually one sees fewer, sometimes none. Titan, the brightest, is two magnitudes dimmer than the faintest of the four conspicuous moons of Jupiter; and the next brightest, Rhea, is nearly two magnitudes fainter than Titan. Titan revolves around Saturn in a little less than 16 days, Rhea in four and a half days. These facts show the observer about what to expect. Often a faint star many light-years beyond Saturn may be mistaken for one of the moons unless a thorough study is made.

Features to Notice with the Telescope: (1) The fact that Saturn shows size and shape, proving that it is not a star but an object in our own system. (2) The centrifugal bulging of the equatorial regions. (3) The rings; especially their brilliance, their inclination, any divisions that you can detect, and their sizes as compared with Saturn's diameter.

THE EARTH AS VIEWED FROM SATURN

Readers interested in the heavens so often ask what the earth would look like if viewed from one body or another that it may be instructive to consider briefly how an answer to such a question

can be obtained. Viewed from the distance of Saturn, the earth would be a mere speck filling 1/81 as large an area of the sky as Saturn does for us. The relative sizes of the two bodies tell us that at once. Further, the earth, on account of its greater proximity to the sun, receives 91 times as much light per square mile as Saturn does. But Saturn has 81 times as many square miles of surface as the earth. Hence the total amount of light received by Saturn is nearly as great (89%) as that received by the whole earth.

Of the light received, the earth reflects back into space about 45% (a result found by studying the earth-lit new moon) and Saturn 42%. Therefore Saturn reflects 42/45 of 89%, or about 83% as much light as the earth does.

But when Saturn is most favorably placed for observation the earth is between it and the sun; whereas when the earth turns its entire sunlit face to Saturn it is on the opposite side of the sun. Thus Saturn is closer to us in the one case, than we are to Saturn in the other, the difference being the distance across the earth's orbit. The ratio of the distances is found to be 1.23, and since the illumination decreases as the square of the distance we must square this factor to find its effect, and thus get 1.51.

Therefore, if distances alone mattered, Saturn would send us about half again as much light as the earth sends it, which more than compensates for the fact that it reflects into space only 83% as much light as the earth does. Taking 83% of 1.51 we get 1.25, our final result. Saturn, then, gives us 1¼ times as much light as the earth sends to it. Using the magnitude system, we find that Saturn appears 0.24 magnitude brighter than the earth, in the favorable positions mentioned above. Saturn's average brightness is 0.36 when so situated. Hence the earth's would be 0.36 plus 0.24, or 0.60 magnitude. This is brighter than the star Altair but not as bright as Vega.

A similar analysis shows that the moon would send to Saturn only 1.2 percent as much light as the earth, and would appear 4.8 magnitudes fainter. Its magnitude would be 5.4. Since this is brighter than a star of the sixth magnitude, our moon would be visible to the naked eye from Saturn *if it were not so close to the earth*. The two would blend into a single point of light, but could be separated with a magnifying power about one-third as great as we require to turn Saturn from a point into a sizable disk.

When so viewed the earth and the moon would make a pretty pair, and in a powerful instrument the earth could be seen passing through phases somewhat similar to those that the moon shows us. With this picture in mind, and an eye at the telescope, we comprehend the more vividly the great stretches of space through which Saturn's light brings us the news of its splendor.

URANUS, NEPTUNE, AND PLUTO

With the outer planets we shall deal but briefly. All are tremendously remote as compared with the sun, though near by the scale of the stars. Cold, feebly lighted, utterly inhospitable to life, they plod their dreary way around the sun at a funereal pace, the outermost, Pluto, moving less than three miles a second and allowing two and a half centuries to pass away while it completes one of its long and cheerless voyages. Long seasons, surely, at sixty-two years each—but what are summer and winter on a planet whose surface temperature is nearly four hundred degrees below the Fahrenheit zero and whose sun to an unaided eye would be a point of light one sixteen-hundredth as bright as the sun's glowing disk appears to us?

The histories of Herschel's discovery of Uranus and of Leverrier's brilliant prediction of Neptune's existence and position are

familiar to one who has read Chapter 2. Pluto was discovered in 1930 at the Lowell Observatory, after a 25-year search.

Uranus when brightest, and if the sky is clear, is just barely visible to the naked eye; Neptune and Pluto are telescopic objects only. A few facts about them — some marked as subject to revision — are included in Table 1. Outside of the great observatories these distant relatives of the earth are of little interest except as examples of the extreme conditions which are possible in a planetary system and because they show how surely the sun controls its satellites across those great reaches of empty space.

ECLIPSES OF THE SUN AND MOON

The planets and their satellites, being opaque, carry shadows around with them. The dense part of the shadow is a long slender cone which each body wears like a dunce cap pointed always directly away from the sun. Into this dense shadow, called the *umbra,* no sunlight penetrates except a little bent into it by the atmosphere if the body possesses one.

Around the umbra is a broader region of partial shade, called the *penumbra,* which flares out from the planet in the shape of a megaphone whose narrower end is fitted on the planet. Any point of the penumbra receives light from a portion of the sun's disk. An eye situated in the penumbra would see part but not all of the sun's disk; from a point in the umbra the entire disk would be invisible.

When the moon gets into the earth's shadow, a lunar eclipse occurs. When the moon's shadow touches the earth a solar eclipse results. When one of Jupiter's moons enters Jupiter's shadow the sunlight is cut off from it and we cannot see it.

The moon can be eclipsed only at the time of full moon; the sun

only at new moon. This will seem obvious if one considers the cause of the new and full phases and reflects that the sun, moon, and earth must be in line to produce an eclipse. The only reason we do not have an eclipse of the sun at *every* new moon is that

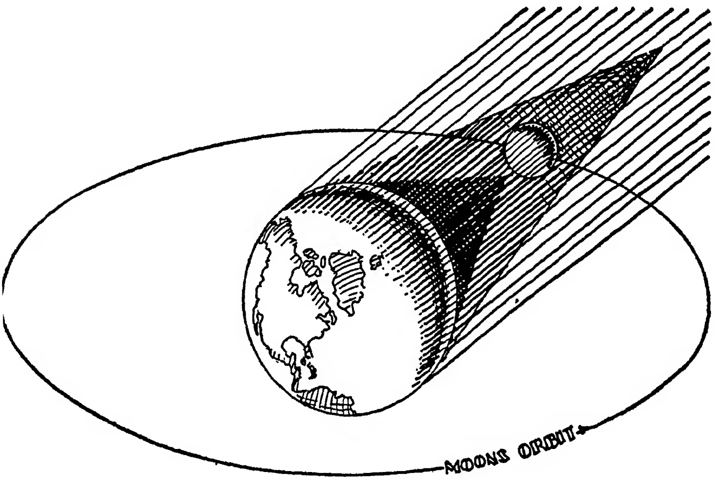


FIGURE 94. The moon in the earth's shadow. Note the two shadows cast by the earth, one the umbra (dense), the other the penumbra. The earth's shadow is so large that an eclipse of the moon may last two hours or more; but when conditions are reversed (moon between sun and earth) the eclipse of the sun is never visible for more than a few minutes at any one locality. (Drawing from *An Introduction to Astronomy,* by Robert H. Baker.)

when the moon gets between the earth and the sun to produce the new phase it usually passes a little to one side of the line joining the earth and the sun.

The greatest number of total eclipses in one year, counting both solar and lunar, is seven. The minimum number is two. At first thought one might suppose that a person would have frequent opportunities to witness these interesting phenomena. But not so:

the greatest possible width of the moon's umbra at the distance of the earth is 167 miles. Usually it is narrower. Thus the tip of the moon's shadow flicks only a small region as it glides across the surface of the earth at a speed ranging from 1000 to 5000 miles per hour.

So nearly does the moon's disk fit the sun, as seen from the earth, that the greatest possible duration of totality in a solar eclipse is 7 minutes 40 seconds. Sometimes the tip of the moon's shadow falls short of the earth though pointed directly at it. Then an annular eclipse of the sun occurs, the middle portion being covered. If one were free to travel to any part of the earth, land or water, he could see at least two solar eclipses a year; but if he stays in one place he will probably never see one. At a given locality a total solar eclipse is visible once in nearly four centuries. We see why so much excitement attends the opportunity, and why astronomers visit distant points to observe solar eclipses. The non-professional observer will of course not fail to view an eclipse of the sun, even a partial eclipse, when the opportunity comes. An evenly smoked piece of plate or of window glass, or, better still, a camera film which has been exposed and developed, is all the equipment one needs to enjoy one of the most impressive of astronomical spectacles.

Total eclipses of the sun are actually more numerous than those of the moon, but *at a given place* the chances of seeing a lunar eclipse are vastly greater. This is because a lunar eclipse is visible from a full half of the earth. The diameter of the earth's dense shadow, or umbra, averages 5700 miles at the distance of the moon. Thus there is ample leeway — a much larger shadow, and a smaller body to pass through it, than in the case of a solar eclipse. A total eclipse of the moon is so long-drawn-out a proceeding that before it has ended, the rotation of the earth has turned many addi-

tional observers into the night where they can witness the latter stages.

The maximum duration of totality in a lunar eclipse is about 1 hour 40 minutes; and the preliminary stages while first the faint penumbra, then the umbra advances across the moon's disk, are even longer. The moon does not completely disappear even at the height of totality; for some light is refracted to it by the earth's atmosphere, suffusing it with a dim copper-colored glow. The moon's surface temperature drops some 300 degrees Fahrenheit while in the shadow—a cold wave, indeed!

The details of eclipses are calculated at least three years in advance and published regularly in the *United States Ephemeris and Nautical Almanac*. From there the predictions find their way into the magazines and newspapers. The agreement of the event with the prediction, to a fraction of a minute, furnishes at every eclipse very impressive proof of the accuracy of our knowledge of the laws governing orbital motion. No longer do civilized people cower in fright when the sun is eclipsed, or make strange vows, or stop wars as the Medes and the Lydians did in 548 B.C. Science has banished the terror.

APPENDIX

TRUE–FALSE REVIEW

This true-false review contains truth and error in about equal proportions. To pick the errors out can easily become an interesting and fruitful exercise. By using 25 or 50 items at a time, the reader can quizz himself at regular intervals and thus test the effectiveness of his reading. Informal round-table discussions can also be arranged. Many of these true-false items require independent reasoning based on principles or on clear mental pictures of the state of affairs in our physical environment, and the discussion can be gotten off to a flying start by the simple expedient of presenting such an item and then asking *Why* no matter whether the reply is *True* or *False*. Another good plan the reader might try is to give himself the true-false quizz on a given unit both before and after reading that unit, and compare the results.

No scoring key is included in this book. Many of the items are answered explicitly in the text. Any doubt about the others (those requiring independent reasoning) can usually be resolved by re-reading the relevant passages in the book and by debating the point at issue with fellow-readers. *But remember that even if a group of fellow-readers all agree on a given answer, that answer may still be wrong.* If, after thorough debate and re-study, the reader feels that there is even a slight possibility that his judgment may be wrong, the only safe plan to follow is to *suspend judgment* until the nearest authority can be consulted.

In scoring results, subtract *double* the number of incorrect judgments from the total number, then divide the result by the total number. This corrects reasonably well for the probability of avoiding errors by chance, and gives the earned average in percent.

TRUE-FALSE REVIEW: PART 1

(See Unit 1; also, for several items, Chapter 1)

1. The age of electric power began with Galileo.
2. Aristotle and Plato were contemporaries.
3. The discovery of x-rays threw thousands out of employment.
4. Michael Faraday and Shakespeare were contemporaries.
5. Tycho Brahe was the true discoverer of Kepler's laws.
6. Science enables man to violate the laws of nature.
7. Humanity's failure to reap the maximum benefit from scientific discoveries is due to a weakness in the scientific method.

The Attitude of an Exact Science is characterized by:

8. Reliance on observation;
9. An inclination to experiment under controlled conditions when possible;
10. Unquestioning acceptance of the opinions of great men;
11. A desire to coerce nature by imposing laws;
12. Willingness to reject or modify hypotheses;
13. A tendency to exalt observed facts above general relationships;
14. A desire to dictate ethical standards of human conduct;
15. Reluctance to undermine popular beliefs regarding nature;
16. A belief that natural actions have natural causes;
17. Willingness to reject observed facts on philosophical grounds;
18. Refusal to accept compilations of unrelated facts as science.

19. If Kepler's laws of planetary motion had been discovered earlier, the planets could have gotten off to an earlier start.
20. If the history of the discovery of Kepler's laws is typical, an exact scientific law summarizes compactly a wealth of information which otherwise would require voluminous statistics.
21. The laws of physics do not apply to living matter.
22. Aristotle's analysis of falling was based partly on observation.
23. Perfection is one of the recognized physical properties of certain kinds of matter.
24. Aristotle's mistake about falling bodies was due principally to lack of funds with which to secure experimental equipment.
25. If the Aristotelian approach to falling bodies is typical of Greek

thought, the Greeks cannot rightly be called the founders of experimental science.

26. The fall of Rome cut short Plato's efforts to correct Aristotle's errors.
27. Aristotle's mistake about falling bodies proves that the best Greek minds were inferior to our best.
28. Luther's protestant reformation was indirectly inspired by Galileo's boldness in breaking with the Aristotelian tradition.
29. The result of Galileo's experiment at the tower of Pisa undermined the philosophy which had led Aristotle to his view of falling.
30. Copernicus merely elaborated the planetary views which Ptolemy had clearly foreshadowed centuries earlier.

TRUE–FALSE REVIEW, Continued — (See Page 661)

31. Ptolemy's astronomical errors could have been discovered as easily as Aristotle's mistake about the falling of light and heavy bodies.
32. Even without instruction or analysis, anybody ought to be able to see that it is the earth's rotation that causes the sun to rise.
33. The great size of Jupiter's moons was the principal reason why Galileo's discovery of them was so important.
34. If the burning of Giordano Bruno had been a lynching it would have less significance in the history of thought.
35. The executions of witches in Salem were the result of one last attempt to maintain Ptolemy's views against those of Copernicus.
36. Galileo did not discover why bodies fall.
37. Isaac Newton discovered magnetic attraction.
38. The acceleration of a falling body is due principally to the increase of the gravitational force on it as it nears the earth.
39. If the gravitational attraction on a falling body ceased, the body would stop instantly.
40. The reason why Galileo's heavier falling body did not outstrip the lighter was that the same amount of force acted on each.
41. If it were not for air friction, all bodies falling freely at the same place would have equal accelerations.
42. If a train stopped suddenly while an apple that had been tossed vertically upwards in a passenger coach was in mid-flight, the apple would not return to its starting place in the car.

43. Newton's first law of motion might appropriately be called the law of inertia.
44. A baseball weighs considerably less while falling than after it has come to rest on the earth's surface.
45. The falling of a living cat is purely a problem of zoology.
46. The falling of a dead cat obeys the ordinary law of physics.
47. The falling of disembodied life would be a chemical problem.

TRUE-FALSE REVIEW, Continued — (See Page 661)

48. The reason a small tug can move an ocean liner is that the tug possesses the greater inertia of the two.
49. The inertia of a body is proportional to its mass.
50. A body totally unsupported yet not falling would necessarily violate Newton's first law of motion.
51. Gravitation prevents the moon from losing its speed.
52. Gravitation prevents the moon from receding to stellar distances.
53. An indirect method of testing a natural law is to deduce a consequence and then look for the consequence.
54. Newton used an indirect method of proving the law of gravitation.
55. The law of gravitation has never received direct proof.
56. The shape of the earth is one reason why an object weighs less at the equator than at the north pole.
57. If an object ascended 4000 miles above the surface of the earth, its weight would become approximately half what it had been on the surface.
58. An object's mass depends on the quantity of matter it contains.
59. Doubling the mass of each of two bodies increases their gravitational attraction for each other to four times the original value.
60. Doubling the distance between the centers of two bodies increases their gravitational attraction for each other about twenty-fold.
61. Making the changes of #59 and #60 simultaneously leaves the force practically unchanged.
62. The gravitational attraction between two automobiles often causes collisions.
63. Cavendish's efforts to build a set of scales large enough to weigh the earth aroused the opposition of those who still clung to the Ptolemaic theory.
64. An object's weight depends both on its mass and on where it is.
65. The fact that the values of the fundamental constants of nature

depend on the units used shows that the constants have no cosmic significance.

66. An exact law of nature states a relationship between two or more numerically expressible quantities.
67. A knowledge of exact laws of nature is useful as a tool in the search for new knowledge.
68. If numerical data restricted to specific cases of gravitational attraction were to be substituted for a knowledge of the law of gravitation, the college library would be too small to hold the full equivalent of the law.
69. The saving of space in books describing nature is the chief advantage of finding the laws of nature.

TRUE-FALSE REVIEW, Continued— (See Page 661)

70. Galle, not Leverrier, deserves the credit for the discovery of Neptune.
71. After Uranus had been discovered, it did not complete even one revolution before astronomers detected its apparent violation of the laws of planetary motion.
72. The reason a knowledge of the exact laws of nature gives man power is that they indicate how to arrange conditions to produce desired results.
73. A knowledge of the laws of floating may be expected to make possible the design of ships with the certainty that they will not embarrass the designer by sinking at the time of launching.
74. Scientific descriptions which do not lend themselves to the calculation of results cannot be considered exact laws.
75. An object halfway between the earth and the moon would be attracted equally by the two bodies.
76. The pouring of a tumbler of water from a pitcher would present gravitational difficulties at that point between earth and moon where their attractions for the water were equal and opposite.
77. The moon's diameter is between ¼ and ⅓ of that of the earth.
78. The earth's diameter is between 7000 and 9000 miles.
79. Viewed from the moon, the sun would be a mere point of light.
80. The sun's distance from the earth is within 50% of 2 light-years.
81. Knowing the moon's actual size and the distances of sun and moon, one can readily tell by looking at the two that the sun is many times as large as the moon.

82. The sun's real diameter exceeds the moon's by about as many-fold as the sun's distance from us exceeds the moon's.
83. Physically, the sun is similar to stars as a class.
84. Planets shine by reflected light.
85. The fact that Polaris is the north star proves that the velocities of the stars are controlled by the earth.
86. At the equator one would find Polaris overhead.
87. The reason Polaris is never visible from Buenos Aires is that it is above the horizon only in the daytime.
88. The altitude of Polaris above the north horizon is equal to the latitude of the locality of the observer.
89. The earth's motion in its orbit causes the mean solar day to be slightly longer than one complete rotation of the earth.
90. A star that is 20 degrees from the north star never sets as seen from Chicago.
91. The earth's rotation on its axis is the cause of the rising and setting of those stars that do rise and set.
92. Any star that rises must also set, for a given locality.

TRUE-FALSE REVIEW, Continued — (See Page 661)

93. If sunlight could be completely cut off from the earth at noon we could see stars in the daytime.
94. A star in the zenith at noon at Philadelphia cannot be seen from that city twelve hours later.
95. The earth's motion in its orbit is what causes stars to rise earlier every night.
96. A star that rises in the southeast will set in the northwest.
97. A star that rises due east at noon will be near the zenith at 6:00 P.M.
98. A star that rises at 8:00 P.M. October first will rise about 6:00 P.M. November first.
99. The earth's rigidity requires that its surface speed, in miles per hour, be the same at all latitudes.
100. The difference between the earth's equatorial and polar diameters is less than one percent.
101. The earth's equatorial bulge is the result of its orbital motion.
102. The earth's upward reaction to the high-jumper's downward push must be the force that sends him up.
103. An airplane propeller spinning in a vacuum would exert no propulsive force.

104. When the exploding powder exerts a certain average forward force on the bullet, it exerts an equal average backward force on the rifle.
105. If the rifle and its bullet had equal inertias, one could not discharge the gun in the usual manner without shooting himself.
106. A body loses its weight when falling freely.
107. A body loses its weight when floating in water.
108. If the cables supporting a freight elevator suddenly snapped, allowing it to fall freely, a 500-pound box of freight that had been resting on the floor of the elevator would not press appreciably against the floor during the descent.

TRUE–FALSE REVIEW, Continued — (See Page 661)

109. If a person were weighing himself on spring platform scales in an elevator, the scales would indicate more than his true weight when the elevator started up.
110. In a similar weighing, the indication would be more than his true weight when the elevator suddenly slowed on the way up.
111. If a flywheel bursts as a result of centrifugal force, the fragments tend to fly radially outwards from the center.
112. It should be possible to test the cohesive strengths of materials by experiments involving rotation.
113. If the earth were not rotating we should seem to weigh at least twice as much as at present.
114. Stars may come apart if they spin rapidly enough.
115. A freely rotating body spins faster when it contracts.
116. If a nebula not originally in rotation contracted, the contraction alone would cause it to begin rotating.
117. The statement that the moon has no atmosphere is a reasonable guess.
118. At sea level, atmospheric pressure on earth can support a column of water about 60 feet high.
119. Barometers are devices for measuring the humidity of the air.
120. The weight of the earth's atmosphere is about equal to that of a sea of mercury that would completely cover the earth to a depth of 34 feet.
121. Carbon dioxide is one of the most plentiful of the gases composing the atmosphere.
122. Carbon dioxide is of no benefit to humanity.

123. Vegetable life restores free oxygen to the atmosphere.
124. Nitrogen is not very active in the chemical sense.
125. If the earth rotated faster, day and night temperatures would tend to become more nearly equal.
126. If the earth had its present mass but the moon's size, objects would weigh more here than they do.
127. If the earth had its present size but a mass equal to the moon's, objects would weigh more here than they do.
128. A one-pound body may weigh either an ounce or a ton, depending on where it is.
129. On the moon, one could kick a massive stone along the ground without running much risk of hurting one's toe.
130. If Deimos revolved around Mars in the same time that Mars rotates on its axis, Deimos would always remain above one certain region of Mars' surface no matter what the plane of its orbit.
131. The moon has thrown its atmosphere off by centrifugal force.
132. Both the size and the mass of a planet help to determine how much atmosphere it can retain.

TRUE-FALSE REVIEW, Continued — (See Page 661)

133. The earth's distance from the sun influences its ability to retain an atmosphere.
134. A hot atmosphere escapes more readily than a cold atmosphere.
135. If the moon did not rotate on its axis we should see its whole surface in the course of a month.
136. A temporary shielding of the moon from the sun's gravitation during an eclipse of the sun would explain the loss of the moon's atmosphere.
137. When the moon comes exactly between the earth and the sun, an eclipse of the sun must result for the earth.
138. Except during lunar eclipses, half of the moon is always sunlit.
139. The new moon is near the eastern horizon at sunrise.
140. When we are having a new moon, China is having a full moon.
141. The earth, if viewed from the moon, would show the cresent phase when we are seeing a moon aged 17 days, counting from the moment when the moon is exactly new.
142. Artists who paint Christmas cards showing stars between the horns of a crescent moon have not erred for all latitudes on the earth.

143. The fact that the moon can hold solid objects but not an atmosphere shows that the velocity of escape is greater for gases than for solids.
144. Doubling the number of revolutions per second and halving the radius of the circle in which a body is whirling quadruples the centrifugal force.

TRUE–FALSE REVIEW, Continued— (See Page 661)

145. The fact that gases exert pressure in all directions is the result of molecular motion.
146. Lack of an atmosphere tends to equalize day and night temperatures.
147. Lack of an atmosphere causes the moon's surface to be eroded more rapidly than the earth's.
148. Bodies would fall more rapidly on the moon than here.
149. The law of gravitation must be very different on the moon.
150. The moon is a noisy place.
151. The moon's whole equatorial zone is always tremendously hot.
152. The principal reason why the earth's atmosphere exerts less pressure at greater heights is that matter simply weighs less farther from the center of the earth.
153. The greater the atmospheric pressure, the more readily water in an open vessel boils.
154. The highest mountain summits lie above the top of the atmosphere.
155. About half the mass of the atmosphere lies below the 3.5 mile level.
156. Twilight is caused by sunspots.
157. On the moon twilight lasts a long time.
158. Meteors are missiles projected at us by explosions on the moon.
159. Meteorites are more numerous than meteors.
160. The total number of meteors striking the earth's atmosphere in 24 hours is nearer millions than thousands.
161. Meteors would be much brighter if the earth had no atmosphere to impede their motion.
162. The fact that the moon revolves around the earth shows that the earth attracts it more strongly than the moon attracts the earth.
163. The fact that the sun appears red when setting shows that the rotation of the earth controls the sun's temperature.

164. The fact that the sun appears oval at sunset proves that man is most susceptible to hallucinations when the sun is on the horizon.
165. The time of full moon is always the best time to sell mining stocks.
166. White light is composite.
167. Colored light-filters add certain wave lengths to the original beams of light.
168. The earth's speed in its orbit is between 15 and 25 miles per second.
169. The distances of the stars are such that an astronomer can be an eye-witness of phenomena of many different centuries.
170. If the sun's gravitational attraction on the earth were not exactly equal and opposite to the centrifugal force associated with the earth's orbital motion, the earth's distance from the sun would change.
171. The sun's gravitational attraction keeps the earth moving.
172. The energy of water power was once part of the sun's energy.
173. The energy of an electric lamp is traceable to the sun.

TRUE-FALSE REVIEW, Continued — (See Page 661)

174. The nebular hypothesis of the evolution of the solar system was suggested by Darwin's biological views.
175. If the solar system had been formed as described in the nebular hypothesis, either the sun would be spinning much faster than it does or the planets would be revolving much more slowly than they do.
176. The saltiness of the sea is due largely to meteorites.
177. The discovery of radioactive sources of energy weakened the contraction theory of the sun's heat.
178. The discovery of radioactivity invalidated both of Kelvin's methods of calculating the earth's age.
179. Even a carefully calculated result can be no more reliable than the assumptions on which the calculation was based.
180. Scarcity of mathematically exact laws in the literature of a given science is no reason for disregarding its results.
181. The discovery of radioactivity provided a reliable method of determining the age of rocks.
182. The theory that the moon is the principal cause of the tides is a plausible guess.

183. The reason why the tides follow the moon is that the moon's gravitational attraction for the earth is greater than the sun's.
184. If the earth had no moon, it would have no tides.
185. If the moon were closer to us, tides would be higher.
186. The tides on Mars must be enormous.
187. Tides are caused by the different gravitational pulls on different parts of the earth.
188. The moon repels the part of the earth that is farthest from the moon.
189. One reason why the moon's tidal effect is greater than the sun's is that the distances from the center of the moon to the nearest and farthest points of the earth differ by a greater percentage than the corresponding distances from sun to earth.

TRUE-FALSE REVIEW, Continued— (See Page 661)

190. The probability argument based on the directions in which the planets and planetoids revolve furnishes proof that the solar system is not a chance aggregation of bodies.
191. The conclusion of that probability argument does not of itself preclude a supernatural origin of the solar system.
192. The planetesimal hypothesis is about two centuries old.
193. If vigorous tidal action is to occur, the two heavenly bodies must approach each other close enough to let the diameter of one of them become appreciable in comparison with the distance between the two bodies.
194. When two bodies are raising tides on each other, the bulges tend to appear near the line joining the centers of the two bodies.
195. As one body moves past the other, the line joining their centers rotates.
196. If Congress should enact a law declaring the planetesimal hypothesis true, the hypothesis would be proved.
197. The earth's age is nearer billions than millions of years.
198. The fact that a certain action may have occurred and must sometimes occur is proof that it did occur in a given case.
199. The planetesimal hypothesis forces us to believe that our own is the only system of planets in the universe.
200. Regardless of hypotheses, the appearance of the sky when cloudless proves that the universe is blue.

TRUE-FALSE REVIEW: PART 2

(See Unit 2)

201. Energy is the capacity for doing work.
202. According to physics, whatever makes one tired is work.
203. Sir James Barrie's conception of work was the same as that of physics when he said that nothing is work unless one would rather be doing something else.
204. Thales and Plato were contemporaries.
205. Jesus antedated Thales.
206. Aristotle and Plato were contemporaries.
207. Galileo and Plato were contemporaries.
208. Plato believed that the immediate evidence of man's senses is the only trustworthy knowledge.
209. Plato discovered the law of gravitation.
210. Plato discovered conservation of energy.
211. Plato believed in the reality of ideas.
212. Plato encouraged thinking about general principles.
213. Archimedes antedated Plato.
214. One reason why Plato looms large in the history of thought is that he stressed the importance of truths which transcend the immediate evidence of man's senses.
215. Plato believed that anything which cannot be seen is not real.
216. Plato believed that anything that can be seen is an imperfect counterpart of the highest form of reality.

TRUE-FALSE REVIEW, Continued — (See Page 661)

217. The death of Hypatia marked an abrupt transition from one school of scientific thought to another.
218. The death of John Huss definitely ended an important scientific development.
219. Dividing the history of thought into periods of exactly 1000 years each is more nearly a convenience than a logical necessity.
220. The most egocentric form of idealism implies that one creates everything that he sees, reads, hears, or touches.
221. The forerunners of science in ancient Greece gave greater weight to philosophical debate than they did to scientific experimenting.

222. At least 20 exact and general laws of physical science were discovered during the 1000 years which ended in 415 A.D.
223. No exact laws of physics were known before 415 A.D.
224. If a statement concerning physical phenomena is not both exact and general, physical science does not dignify it by the name of law.
225. Knowledge of a physical law enables scientists to predict what will happen under given conditions in a field of action covered by that law.
226. An exact and general law of nature states a relationship between two or more philosophical theories.
227. Plato did not encourage scientific experimentation.
228. Plato did not discover any exact laws of nature.
229. One reason why Plato's ideas should interest a student of the history of science is that, among the great thinkers of the world, he was one of the earliest to emphasize that isolated facts alone cannot give a complete knowledge of physical reality.

TRUE–FALSE REVIEW, Continued — (See Page 661)

230. The buoyant force on an iron ball floating freely in mercury exceeds the ball's weight.
231. The weight of the liquid displaced by a freely floating body is the same no matter what liquid it is floating in.
232. If the Atlantic Ocean were composed of kerosene oil, the *Normandie* would ride higher than it does now.
233. Since the specific gravity of mercury is 13.6 (i.e., mercury is 13.6 times as dense as water) a ball which displaces 1000 cubic inches of liquid when floating in water, will displace only 73.5 cubic inches when floating in mercury.
234. An automobile loses some of its weight when submerged in water.
235. People lose all their weight when floating in water.
236. Water shields a floating object from the earth's gravitational attraction.
237. If a heavy sinker is weighed with a dependable spring balance while submerged in water, the apparent weight indicated by the balance equals the difference between the sinker's true weight and the buoyant force of the water.
238. If a person holding a heavy sinker is weighed with a dependable spring balance while submerged in water, the weight of the

water displaced by the person equals the weight of the person *plus* the apparent weight of the sinker when weighed in water *minus* the upward pull of the spring balance.

239. In the same case, the average specific gravity of the matter composing the person's body can be found by dividing the person's weight by the weight of the water displaced by his body.
240. The accuracy of the preceding statement would be improved if "the person's height" were substituted for "the person's weight."
241. If a person's average specific gravity is less than 1.00, he floats in water without effort.
242. The buoyant force on a rigid airship of the Zeppelin type increases as the ship ascends to higher altitudes.

TRUE–FALSE REVIEW, Continued — (See Page 661)

243. George Washington discovered the law of the lever.
244. The number of years since the discovery of the law of the lever is nearer to 2200 than to either 3200 or 1200.
245. Many exact and general laws of biology were already known when the law of the lever was discovered.
246. The law of the lever may be regarded as a special case of Archimedes' principle of buoyancy.
247. The relation between those two laws is chiefly historical.
248. Levers enable man to frustrate the law of conservation of energy.
249. If the long arm of a lever is 20 times as long as the short arm, every pound-weight of force applied to the long arm can counterbalance about 20 lbs-wt. at the short arm.
250. With the same lever, the work accomplished will be about 20 times the energy supplied by the agency which actuates the lever.
251. Christopher Columbus was the first to propose the idea that the earth is round.
252. Zosimos captured Rome.
253. Zosimos was one of the earliest known alchemists.
254. Chemistry as a science had its beginnings in alchemy.
255. Chemistry as an art or craft antedated Christianity.
256. Chemistry as an art or craft antedated Thales.
257. So far as is known, Zosimos discovered no laws of chemistry.
258. The idea that characterized alchemy was the possibility of transmuting one element into another.
259. The artificial transmutation of elements has recently been accomplished.

260. The earliest alchemists distinguished accurately between elements and compounds.
261. The interval from Zosimos to Galileo is longer than that from Galileo to the present.
262. Zosimos antedated Geber.
263. Geber antedated Roger Bacon.
264. Christopher Columbus and Leonardo da Vinci were contemporaries.
265. Leonardo da Vinci antedated Galileo.
266. Claudius Ptolemy antedated Copernicus by about 13 centuries.
267. Copernicus antedated Einstein (of relativity fame) by about 4 centuries.
268. Zosimos antedated Charlemagne.
269. Galileo and Shakespeare were both born in 1564.
270. Newton was born the year Galileo died.
271. Newton was born the year Nero died.
272. Newton antedated Benjamin Franklin.

TRUE-FALSE REVIEW, Continued—(See Page 661)

273. Accurate thermometers have been available for about 10 centuries.
274. If a thermometer's glass bulb expanded more than the mercury, the higher numbers would be at the bottom of the scale.
275. Use of the Fahrenheit scale requires that water be made hotter to boil than if a centrigrade scale is used.
276. Temperatures of incandescent objects can be measured without making a thermometer very hot.
277. Nature abhors a vacuum.
278. A vacuum expands when heated.
279. Torricelli was obliged to invent an air-pump in order to perfect his barometer.
280. Barometers of the Torricellian type are of purely historical interest today.
281. Torricelli's barometer was made before Fahrenheit's thermometer.
282. The presence of any air above the mercury would be more serious in a barometer than in a thermometer.
283. These two instruments merely apply the same physical action in different practical applications.
284. Gutenberg's improvements in printing antedated the barometer.
285. If some air is squeezed by pouring mercury into one arm of a U-tube whose other arm is closed at the top, the atmospheric

pressure must be taken into account in figuring how much pressure the trapped air is subjected to.

286. A barometric reading that is abnormal at one place is necessarily abnormal at another place.
287. If two airships of the lighter-than-air type are identical except that one is rigid but the walls of the other can stretch readily, and if the two, after being released simultaneously, experience no leakage, accidents or artificial control, the non-rigid ship will rise higher than the other.
288. In the same case, the non-rigid ship will leave the atmosphere.

TRUE-FALSE REVIEW, Continued — (See Page 661)

289. During a prolonged run at high speed, the air in leak-proof automobile tires is appreciably warmed.
290. In the same case, the air's pressure increases appreciably.
291. In the same case, the air's volume increases appreciably.
292. In the same case, the air's mass increases appreciably.
293. In the same case, the air's density increases appreciably.
294. If the temperature of a confined mass of gas remains constant, tripling the pressure triples the volume.
295. In the same case, doubling the pressure halves the volume.
296. In the same case, halving the pressure doubles the volume.
297. If the last two statements are true, the volume is inversely proportional to the pressure at constant temperature.
298. Two times 12 equals 24.
299. Four times 6 equals 24.
300. Eight times 3 equals 24.
301. If one quantity is inversely proportional to another, their product remains constant.
302. Boyle's law and universal gravitation were discovered in the same century.
303. To speak of doubling the temperature of anything is indefinite unless the whole temperature above absolute zero is meant.
304. Charles' law was discovered by Archimedes.
305. Momentum is the same as kinetic energy.
306. A force less than its weight can stop a freely falling locomotive if sufficient time is allowed.
307. The force exerted when a coasting locomotive is brought to rest by an obstacle depends on the suddenness of the stop.

308. The effectiveness of the fireman's net is due chiefly to the softness of the cords of which it is made.
309. Momentum equals mass times velocity.
310. Anything that cushions a fall would necessarily be a poor take-off for a broad jump.

TRUE-FALSE REVIEW, Continued — (See Page 661)

311. When a stone is thrown vertically upwards (air friction being negligible) *doubling the starting velocity* doubles the starting momentum;
312. . . . and doubles the starting kinetic energy;
313. . . . and doubles the height of rise;
314. . . . and doubles the time of rise;
315. . . . and doubles the temperature of the stone;
316. . . . and doubles the potential energy which the stone will have just before it starts to fall back;
317. . . . and doubles the kinetic energy which it will have when it returns to ground;
318. . . . and doubles the momentum which it will have when it returns to ground;
319. . . . and necessarily doubles the force which it will exert on landing;
320. . . . and doubles its density;
321. . . . and doubles the bodily energy expended by the thrower.
322. Increasing the velocity of an automobile by 10% increases its kinetic energy by much more than 10%.
323. The work done when an object is lifted vertically equals its weight multiplied by its speed.
324. If a 150-pound man is lifted 300 feet vertically by the elevator in a skyscraper, the number of foot-pounds of work done on the man is nearer to 50,000 than to either 500 or 500,000.
325. When a pound of hot water is poured into a cold aluminum pan weighing one pound, the fact that the pan's temperature rises more than the water's falls shows that aluminum has a smaller thermal capacity, or specific heat, than water has.
326. If, with regard to change of volume when freezing, water behaved as most metals do, icebergs would ride higher than they do now;
327. . . . and fish would not thrive in Minnesota lakes.
328. Lavoisier antedated Robert Boyle.

329. Lavoisier was one of the leaders of the French Revolution.
330. Lavoisier was a contemporary of Count Rumford.
331. Lavoisier established the principle of conservation of mass.
332. Lavoisier died about 1½ centuries later than Galileo.
333. Lavoisier did his work before the time of the chemical balance.
334. Lavoisier combated the phlogiston hypothesis.
335. Lavoisier combated the caloric hypothesis.
336. Count Rumford was one of the leaders of the American Revolution.
337. If Count Rumford had measured the specific heat of brass in both the massive and the powdered form, he could have refuted the calorists' objection to the conclusion which he drew from his cannon-boring experiment.
338. The result of Sir Humphry Davy's ice-rubbing experiment proved conclusively that friction produces heat.

TRUE–FALSE REVIEW, Continued — (See Page 661)

339. Joule's determination of the mechanical equivalent of heat established the principle of conservation of energy;
340. . . . and proved the impossibility of perpetual motion of the sort that many inventors have sought;
341. . . . and proved that the earth cannot continue indefinitely to revolve around the sun;
342. . . . and proved that a man of iron will can for a short time do more physical work per calorie of energy than could a machine of 100% efficiency.
343. The average wattage of an adult human being is nearer to 150 than to either 15 or 1500.
344. In foot-pounds per calorie, the mechanical equivalent of heat is nearer to 30 than to either 3 or 300.
345. The height to which a 4000-pound automobile must rise in order to acquire 3,300,000 calories of potential energy is nearer to 2500 feet than to either 250 or 25,000 feet.
346. Boyle's definition of a chemical element marked a turning point in chemistry.
347. This achievement of Boyle's antedated Newton's *Principia.*
348. Boyle and Benjamin Franklin were contemporaries.
349. Boyle antedated John Dalton.

350. Pure copper is a compound.
351. Pure copper is an element.
352. Pure copper is a mixture.
353. This list names more physical changes than chemical: melting, rusting, combustion, evaporation, dissolving, expansion.
354. This list names more elements than compounds: salt, oxygen, hydrogen, mercury, water, chlorine, sodium, rust, sugar, iron, nitrogen, laughing gas, sulphur, caustic soda, carbon.
355. As a general rule, if a chemical compound is harmless when eaten, the elements of which it is composed may be eaten separately with impunity.

TRUE-FALSE REVIEW, Continued — (See Page 661)

356. A jet of hydrogen can burn in a vessel filled with oxygen.
357. A jet of oxygen can burn in a vessel filled with hydrogen.
358. Water is an oxide of hydrogen.
359. Air is an oxide of nitrogen.
360. Sodium chloride is highly poisonous.
361. The number of atoms in a molecule of hydrogen is nearer to 10^{24} than to 2.
362. These substances are listed in order of increasing numbers of atoms per molecule: carbon dioxide, caustic soda, cane sugar.
363. Dalton discovered the law of multiple proportions.
364. The law of multiple proportions is the same as the law of definite proportions.
365. Dalton discovered the principle of conservation of mass.
366. Dalton was the leader in the scientific movement which established the atomic theory of matter.
367. The interval from Galileo to Dalton was longer than the interval from Dalton to the present time.
368. If oxygen and hydrogen are mixed without measuring in a glass globe, and the mixture exploded, either some hydrogen or some oxygen will, in general, remain uncombined.
369. The number of pounds of combined oxygen in 100 pounds of pure water is the same as the number of tons of combined oxygen in 100 tons of pure water.
370. If 10,000 persons picked at random from the streets of a great city raced to find which could run the farthest in 2 minutes, and if

the distances traversed, when accurately measured, were all found to be exact whole multiples of the length of a certain measuring stick, one would be obliged to suspect that either space or motion was fundamentally discontinuous (atomic) in nature.

371. The fact that the amount of oxygen found combined with 1.751 grams of nitrogen in nitrous oxide is exactly 1.000 gram proves conclusively that oxygen is composed of atoms.
372. The fact that the next larger amount of oxygen that can be found combined with 1.751 grams of nitrogen is exactly 2.000 grams is merely a coincidence.
373. Any amount of any oxide of nitrogen always contains 1.751 grams of combined nitrogen.
374. Any oxide of nitrogen always contains an exact whole number of grams of oxygen for every 1.751 grams of nitrogen.
375. The fact that the proportion of oxygen to hydrogen is as 16.000 to 1.008 in *both* caustic soda and hydrogen peroxide is either a coincidence or the result of identical manufacturing processes.

TRUE-FALSE REVIEW, Continued — (See Page 661)

376. Every chemical action proves that energy is intimately associated with matter.
377. The following men who helped to build the science of chemistry are listed in chronological order, earliest first: Boyle, Cavendish, Lavoisier.
378. And so are these: Black, Avogadro, Priestley, Dalton.
379. Iatrochemistry is the newest development in atomic theory.
380. Molecules of compounds are not the only molecules which contain more than one atom each.
381. When two gases combine to form another gas, the volume of the resulting compound is, in general, the sum of the original volumes.
382. Conservation of volume is one of the laws of chemistry.
383. The idea that matter is atomic will remain a guess until everybody has seen individual atoms with the naked eye.
384. Atoms are as real as planets.
385. The Brownian movement was discovered by Joule.
386. In studying the Brownian movement by eye we actually see molecules moving.
387. The Brownian movement shows that molecules move incessantly.

388. If some air trapped in an insulated cylinder is compressed, the air becomes warmer;
389. . . . and its molecules move faster;
390. . . . and it possesses more energy;
391. . . . and its pressure is increased;
392. . . . and its temperature is reduced;
393. . . . and it can now do more work if allowed to expand;
394. . . . and somewhere else something must have lost energy.

TRUE–FALSE REVIEW, Continued — (See Page 661)

395. The reason why gas shut up in a cylinder exerts an outward pressure is that the molecules repel one another.
396. The kinetic theory of gases leads us to believe that the pressure times the volume of a gas equals ⅔ of the total kinetic energy of the moving molecules.
397. The laws of Boyle and Charles, if combined into one, prove that the pressure of a gas times its volume is proportional to the absolute temperature of the gas.
398. The two preceding items contradict each other.
399. The way to make anything absolutely cold is to make its molecules stop moving.
400. A body at $-200°$ C. is absolutely cold.
401. This list names more cooling than heating processes: compression, expansion, liquefaction, friction, evaporation.
402. Boiling occurs when the vapor pressure of the liquid equals the external pressure.
403. A boiling liquid is necessarily hot.
404. Boiling can produce a cooling effect.
405. Boiling can be produced by reduction of pressure.
406. The reason why dry ice (solid carbon dioxide) disappears without melting is that the heat of the room cannot penetrate the outer layers of the material.
407. Artificial refrigeration is commonly produced by forcing evaporation and condensation to occur successively in different parts of the apparatus.
408. Any substance whose evaporation and condensation can be readily controlled by means of pressure can be used as a refrigerant.
409. If the air blown against the skin by an electric fan is warmer than the skin, it cannot possibly produce a cooling effect.

410. Satisfactory air-conditioning involves both humidity control and temperature control.
411. Evaporation is the action which enables dry ice to keep itself cold until all has disappeared.
412. All heat engines are necessarily very inefficient.
413. Heat cannot be transferred from a colder to a hotter body.
414. Energy can be destroyed.
415. Energy can be degraded.
416. The availability of energy can be destroyed.
417. The statement "The universe is running down" is certainly nonsense no matter what special meaning we assign to *down*.

TRUE–FALSE REVIEW, Continued— (See Page 661)

418. *Before the year 1850,* x-rays were discovered;
419. . . . the atomic nature of matter was proved;
420. . . . conservation of energy was verified;
421. . . . the kinetic nature of heat was proved;
422. . . . transatlantic cables were being used;
423. . . . incandescent electric lamps were available;
424. . . . the existence of electrons was detected;
425. . . . at least four methods of generating electric currents were known;
426. . . . electric motors were widely used;
427. . . . radio was unknown;
428. . . . radioactivity was discovered;
429. . . . laws of electrolysis were known;
430. . . . more than 2000 chemical elements were known;
431. . . . Michael Faraday made his greatest discovery;
432. . . . magnetic effects were known;
433. . . . magnetism could be produced artificially;
434. . . . Volta made his greatest discovery.
435. The fact that many compounds can be broken down into their constituent elements by passing electric currents through solutions proves that matter and electricity are intimately associated;
436. . . . and strongly suggests that the atoms of compound molecules are bound together by electric forces;
437. . . . and proves that matter is composed of electricity;
438. . . . and proves that gravitation is an electric force;

439. . . . and proves that matter and electricity are identical;
440. . . . and proves that electricity is mostly empty space;
441. . . . and proves that inertia is an electric force.
442. Faraday proved that electricity is a liquid.
443. The fact that *one* quantity of electricity (96,500 coulombs) continually recurs in electrochemical calculations based on many *different* atomic weights proves that electricity is essentially discontinuous, or atomic, in nature;
444. . . . and allows at least a reasonable inference that electricity may be more fundamental than matter as a basic physical reality.
445. The facts of electrolysis alone show that if either matter or electricity is atomic, they both are.
446. Cathode rays are high-speed atoms.
447. Cathode rays are the same as x-rays.
448. Cathode rays can produce x-rays.
449. The fact that cathode rays can be deflected by means of a magnet shows that they are made of iron.
450. That fact that cathode rays produce both heat and mechanical shock when they strike a target shows that they are matter in motion.
451. The fact that cathode rays are deflected when passing between two oppositely charged plates shows that they carry electricity.

TRUE-FALSE REVIEW, Continued — (See Page 661)

452. Faraday named positive and negative electricity.
453. Benjamin Franklin named positive and negative electricity.
454. If coldness is regarded as negative hotness, then negative electricity is negative in practically the same sense.
455. Unlike kinds of electricity attract each other.
456. The results of Millikan's oil-drop experiment are sufficient of themselves, without reference to chemical evidence, to establish the atomic nature of electricity.
457. If the charge of an electron were always used as the unit, all possible quantities of electricity would be expressed by whole numbers.
458. The filament of a radio tube is heated for the same purpose as is that of a Coolidge x-ray tube.
459. Coolidge discovered x-rays.

460. Faraday discovered x-rays.
461. The function of the high-voltage applied to a Coolidge x-ray tube is to liberate electrons;
462. . . . and to push aside the matter which obstructs the path between filament and target.
463. If we say that the grid stationed between filament and plate in a typical three-electrode radio amplifying tube acts as a traffic regulator, the implications are reasonably accurate.
464. High-speed ionized atoms of helium can be detected individually by eye.
465. Spinthariscopes are always made out of coffee cans.
466. Radium is the only radioactive element known.

TRUE-FALSE REVIEW, Continued — (See Page 661)

467. Madame Curie discovered radium.
468. Henri Becquerel discovered radium.
469. Roentgen discovered radium.
470. The disintegration of radioactive elements obeys no known law.
471. Radioactivity is an example of the transmutation of elements.
472. Medieval alchemists knew of radioactivity.
473. Chance is one of the known physical agencies which exert forces on matter.
474. The fact that alpha rays shot through the interiors of atoms are seldom deflected proves that atoms are filled with liquid.
475. Interference phenomena are a test for wave motion.
476. The fact that a soap bubble appears various colors when viewed by white light proves that the soap was defective.
477. When a lamp or cloud is viewed through a slit of suitable narrowness, the appearance of dark lines proves that light consists of waves.
478. If light consisted of continuous waves, the emission of photoelectrons would be delayed for weeks or months after a moderately strong illumination began to bathe the surface atoms.
479. The diffraction of electrons shows that at least some particles possess the properties of waves.
480. A quantum is an atom of uranium.
481. Quantum is another name for electron.
482. Using *atom* in the broad sense implied when we say that electricity is atomic in nature, we may say that a photon is an atom of light.

483. Electrons exert a propulsive force when colliding with objects.
484. Matter exerts a propulsive force when colliding with objects.
485. Light exerts a propulsive force when colliding with objects.
486. Inertia is a property that is common to electricity, matter and radiant energy.
487. Inertia is commonly considered to be one of the basic tests for the existence of matter.
488. Discontinuity is a property that is common to electricity, matter and radiant energy.
489. Every object contains electrons.
490. There are as many different kinds of electrons as of atoms.
491. There are more kinds of protons than of neutrons.
492. Positrons are heavier than electrons.
493. That an atom contains a highly concentrated nucleus has been well established.
494. That atoms contain extra-nuclear electrons has been well established.
495. The Rutherford-Bohr and Lewis-Langmuir models of atomic structure were the earliest attempts to explain neutrons.
496. The most recent atomic model gives a perfect picture of the structure of atoms.
497. There are good grounds for believing that forces of electric attraction play an important role in chemical reactions.
498. It is easy to picture a physical entity which is both energy and matter at the same time.
499. It is easy to picture a physical entity which possesses the properties of both particles and waves at the same time.
500. The human mind can discover a reality which it cannot picture.

TRUE–FALSE REVIEW: PART 3

(See Unit 3)

501. The original theoretical development which led to Marconi's most important contribution to civilization took place in the field of pure science;
502. . . . and was recognized by the man who achieved it to be the foundation of practical broadcasting;
503. . . . and was first published about the time of the American Civil War;

504. . . . and immediately influenced inventors the world over to undertake practical experimenting;
505. . . . and showed that light is an electromagnetic phenomenon.
506. Faraday's discovery of electromagnetic induction should be included in any comprehensive history of radio.
507. Edison's discovery of the emission of electricity from hot bodies was one important factor in Marconi's first success in dot-dash wireless telegraphy.

TRUE–FALSE REVIEW, Continued — (See Page 661)

508. Quantitatively, the most important primary source of energy used in doing the world's work is chemical.
509. In the United States as a whole, more of the energy used in doing work comes . . . from petroleum gasoline than from coal;
510. . . . more from natural gas than from water power electricity;
511. . . . more from tides than from gasoline;
512. . . . more from food than from coal;
513. . . . more from winds than from meteors;
514. . . . more from water power electricity than from coal.
515. In energy units, the average daily ration recommended for men who work is nearer to 3,000,000 gram-calories than to either 300,000 or 30,000,000.
516. A gram-calorie is the ordinary calorie usually understood . . . in books of dietetics;
517. . . . in books of chemistry and physics.
518. The average daily ration of energy could be expressed in any one of the following units: kilogram-calories, watt-hours, foot-pounds, ergs, kilowatt-hours.
519. An appropriate calculation which could be performed on the margin of this page would, if correct, show that if every person in the United States regularly consumed the daily ration recommended for able-bodied adults, the annual consumption of food-energy in the United States would be nearer to the figure given earlier for electricity than for gasoline.
520. The three elements which, in combined form, are most plentiful in the human body are . . . oxygen, carbon, iron;
521. . . . oxygen, mercury, phosphorus;
522. . . . oxygen, carbon, hydrogen;

523. . . . nitrogen, calcium, hydrogen.
524. The elements named in 520–1–2–3 include the six elements which are most abundant in the human body.
525. Chloroplasts are utilized principally as a high explosive.
526. Carbon dioxide is one of the most plentiful gases in the atmosphere;
527. . . . and one of the most important.
528. The process known as photosynthesis is a recent invention.

TRUE-FALSE REVIEW, Continued — (See Page 661)

529. Atoms of all these elements — C, H, O — and of no other element, are present in a molecule . . . of glucose;
530. . . . of sucrose;
531. . . . of starch;
532. . . . of water;
533. . . . of carbon dioxide;
534. . . . of cellulose;
535. . . . of fructose;
536. . . . of formaldehyde;
537. . . . of laevulose;
538. . . . of dextrose.
539. Every sugar is an organic compound.
540. Water is an organic compound.
541. Every sugar is a carbohydrate.
542. Glucose and fructose are isomers.
543. Starch and cellulose are isomers.
544. If two compounds are composed of the same elements in the same proportions, they are invariably identical.
545. Fats used as food are good energy-producers;
546. . . . and so are the sugars;
547. . . . and so is water.
548. A reason why the fixation of nitrogen is a matter of great practical importance is . . . that plants require combined nitrogen;
549. . . . that nitrogen is escaping from the earth;
550. . . . that man needs it for breathing purposes;
551. . . . that coal will not burn without nitrogen.
552. Le Chatelier's principle applies to reversible reactions.
553. Van't Hoff's law applies to reversible reactions.

554. If the forward action of a reversible reaction tends to cool the reagents, lowering the temperature at which the reaction occurs promotes the forward action.
555. If the forward action of a reversible reaction tends to reduce the pressure in the chamber in which the reaction takes place, increasing the pressure promotes the forward action.
556. The Haber process produces a substance which is . . . a compound of nitrogen and hydrogen;
557. . . . a useful refrigerant;
558. . . . useful in the manufacture of fertilizer;
559. . . . the principal ingredient of dry ice;
560. . . . useful in the manufacture of explosives;
561. . . . a widely used fuel;
562. . . . included in every well-balanced diet.

TRUE-FALSE REVIEW, Continued — (See Page 661)

563. In a well-balanced diet, vitamins contribute a large share of the energy.
564. Some vitamins act in the body as catalysts.
565. Lean meat is rich in proteins.
566. Milk is an important source of calcium for the human body.
567. Calcium is rich in carbohydrates.
568. Sugar is one of the foods to be recommended for the purpose of re-energizing the human body relatively quickly.
569. Cellulose was the principal raw material out of which coal was formed.
570. Water and carbon monoxide are the two principal raw materials out of which cellulose is formed.
571. At the present rate of consumption, the period during which the underground petroleum resources already discovered in this country may be expected to last is nearer to 40 years than to either 4 or 400.
572. Petroleum is a mixture of hydrocarbons.
573. Petroleum is a mixture of carbohydrates.
574. The reason why air must be excluded from the chambers in which petroleum is being cracked is that the air would retard the process of fractional distillation.
575. In this unbalanced equation showing the combustion of hexane

$2C_6H_{14} + (?)O_2 \rightarrow 12CO_2 + 14H_2O$, the equation could be balanced by replacing the question mark with a number that is nearer to 20 than to either 15 or 25.

576. Using any one of those numbers (15 or 20 or 25) in that manner would imply a violation of the principle of . . . conservation of mass;
577. . . . conservation of volume.
578. If the letters C, H and O represent atoms in that equation, the total number of atoms indicated to the right of the arrow is nearer to 80 than to either 60 or 100.
579. In that equation, CO_2 is the product whose presence accounts for the appearance of a white cloud behind an automobile's exhaust pipe on a very cold day.
580. If that equation gave a complete description of the chemical actions which occur in the cylinder of an automobile, the exhaust would be less dangerous in a closed garage than it actually is.

TRUE–FALSE REVIEW, Continued — (See Page 661)

581. The phenomenon of electromagnetic induction . . . was discovered by Michael Faraday;
582. . . . was discovered less than 150 years ago;
583. . . . was discovered before electric cells were devised;
584. . . . is applied in all dynamo generators;
585. . . . is applied in all transformers;
586. . . . is applied in all dry cells;
587. . . . is applied in all thermocouples;
588. . . . is applied in all photoelectric cells;
589. . . . underlies the usefulness of storage batteries;
590. . . . can be produced by combing the hair with a rubber comb;
591. . . . can be produced by twirling a coil of copper wire between the poles of a U-shaped magnet;
592. . . . can be produced by twirling a coil of iron wire between the poles of a U-shaped magnet.
593. For successful operation in practical applications . . . a dynamo generator must contain at least one moving part;
594. . . . a transformer must contain at least two moving parts;
595. . . . thermocouples need contain no moving parts;

596. . . . an electric motor must contain at least two moving parts;
597. . . . dynamo generators must be supplied with alternating current;
598. . . . transformers must be supplied with rectified current;
599. . . . incandescent lamps must be supplied with direct current;
600. . . . electromagnets used for lifting purposes must be supplied with high-frequency current.
601. In a circuit consisting of an incandescent lamp filament connected in series with the secondary of a transformer . . . any electric resistance offered by copper connecting wires is a detriment;
602. . . . any resistance offered by the filament is a detriment;
603. . . . any voltage-drop in the connecting wires is a detriment;
604. . . . any voltage-drop in the filament is a detriment;
605. . . . any generation of heat in the transformer secondary is a detriment.
606. If a transformer is to be adjudged satisfactory, the amount of energy delivered by its secondary coil must exceed the energy supplied to its primary coil.

TRUE-FALSE REVIEW, Continued — (See Page 661)

607. A reason high voltage is preferred for long-distance transmission lines is . . . that trespassers may be frightened off;
608. . . . that the delivered power may be great and the current in the line relatively small at the same time;
609. . . . that the loss of voltage in the line may be small;
610. . . . that the electrons may be enabled to jump the gaps in the transmission line;
611. . . . that the loss of energy in the line may be small;
612. . . . that there may be no serious delay in the transportation of electrons;
613. . . . that the delivered power may be great without requiring wires of excessive thickness.
614. Doubling the voltage applied to a given resistance of fixed value . . . doubles the current;
615. . . . quadruples the power.
616. If an electromotive force of 110 volts is applied to a lamp filament whose operating resistance is 200 ohms . . . the current drawn by the lamp is nearer to 0.5 ampere than to either 0.05 or 5.0;

617. . . . the power of the lamp is nearer to 60 watts than to either 15 or 100;
618. . . . and the cost of operating the lamp for 8 hours, at 6¢ per kilowatt-hour, is nearer to 4¢ than to either 1¢ or 10¢.
619. Judged quantitatively in terms of energy, electricity is now man's mightiest agency for doing work.
620. The three elements which, in combined form, are most plentiful in the earth's crust are . . . oxygen, silicon, iron;
621. . . . oxygen, aluminum, calcium;
622. . . . magnesium, sodium, potassium;
623. . . . copper, lead, glass;
624. . . . oxygen, silicon, aluminum;
625. . . . coal, sand, clay.
626. The six elements which are most abundant in the earth's crust are included among the substances named in items 620 to 625.

NOTE. This list presents the correct equations of eleven chemical reactions, all of practical importance. A number of comments on these equations will be found below. The point at issue is not the accuracy of the equations, but of the comments which follow them. Detect the incorrect comments.

(a) $N_2 + 3H_2 \rightleftarrows 2NH_3 + 24{,}000$ calories
(b) $HCl + NaOH \rightarrow H_2O + NaCl$
(c) $CaCO_3 + H_2O + CO_2 \rightleftarrows Ca(HCO_3)_2$
(d) $Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$
(e) $2Al + Fe_2O_3 \rightarrow 2Fe + Al_2O_3 + 190{,}000$ calories
(f) $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$
(g) $NaHCO_3 + H_2O \rightleftarrows NaOH + H_2CO_3$
(h) $C + O_2 \rightarrow CO_2 + 97{,}000$ calories
(i) $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$
(j) $C + CO_2 \rightarrow 2CO$
(k) $C_7H_{16} + 11O_2 \rightarrow 7CO_2 + 8H_2O$

627. The substances mentioned in the foregoing list of equations include . . . at least 8 kinds of dynamite;
628. . . . at least 8 organic compounds;
629. . . . at least 8 inorganic compounds;

630. . . . at least 8 substances which are gases under standard atmospheric pressure and at O°C.;
631. . . . at least 4 salts;
632. . . . at least 4 bases;
633. . . . at least 8 electrolytes;
634. . . . at least 2 hydroxides;
635. . . . at least 4 acids.
636. The actions for which no calories are specified in the list of equations do not involve any transformations of energy.
637. An action which helps to energize the human body . . . is (a);
638. . . . is (e);
639. . . . is (k).
640. An action widely used in heating homes . . . is (j);
641. . . . is (h).
642. An action involved in the neutralization of acid stomach with a common medicine is (g).
643. An equation showing why the mortar commonly used in bricklaying does not harden under water . . . is (f);
644. . . . is (c).
645. An action forming a compound used in manufacturing fertilizer is . . . (a);
646. is . . . (d).
647. An action that is useful in welding is (e).
648. An action illustrating unequal chemical activities of metals . . . is (e);
649. . . . is (d).
650. All these actions involve oxidation: (e), (j), (k).
651. All these actions involve reduction: (e), (j), (d).
652. An action which helps to keep the atmosphere supplied with a gas that is essential to plant life is . . . (j);
653. . . . is (h).
654. An action which produces common salt is (f).
655. An action involving an organic vegetable compound is (i).
656. One of the actions involved in the extraction of iron from ore is (j).
657. An action involving limestone is (c).
658. An action widely applied in propelling vehicles . . . is (k);
659. . . . is (i).

TRUE–FALSE REVIEW, Continued—(See Page 661)

660. The normal human eye resembles an adjustable camera with regard to . . . the means of focusing for objects near and far;
661. . . . the general nature of the action which forms the image;
662. . . . the kind (real or virtual) of the image;
663. . . . the orientation (erect or inverted) of the image;
664. . . . automatic adaptation.
665. The concentrated beams of searchlights do not obey the inverse square law of illumination.
666. If a printed page is lighted solely by an electric bulb of 40 candle power, the illumination on the page will be doubled if the lamp's distance from the page is halved.
667. The eye's behavior in changing its sensitivity is one reason why indirect lighting is preferable to direct.
668. If a motion picture of a football game were made at the rate of 24 exposures per second and then projected at the rate of 6 per second, a satisfactory slow-motion reproduction would be achieved.
669. If one glass filter (#1) transmits only monochromatic red light, and another (#2) transmits only monochromatic blue . . . a white lamp will appear red if viewed through #1;
670. . . . a white lamp will be invisible if viewed through both;
671. . . . a screen which appears white in direct sunlight will, if simultaneously illuminated by superimposing two beams of sunlight, one filtered through #1, the other through #2, appear black.
672. If faces were never illuminated with any light other than the nearly monochromatic orange-yellow light which is characteristic of the element sodium, rouged lips would never appear red.

TRUE–FALSE REVIEW, Continued—(See Page 661)

673. If the words *octave, high, low* were applied to the complete electromagnetic spectrum in the same physical senses attached to them in the field of sound . . . the human eye would be adjudged more limited than the ear with regard to range;
674. . . . reds would be called high colors;
675. . . . visible blue would be lower than yellow;
676. . . . yellow would be higher than red;
677. . . . ultra-violet would be deemed lower than gamma rays;

678. . . . ultra-violet would be deemed higher than radio waves;
679. . . . infra-red would be lower than ultra-violet;
680. . . . the so-called short radio waves would be higher than the broadcast band;
681. . . . x-rays would be higher than ultra-violet.
682. If these numbers — 200, 250, 300, 400, 500, 600, 800 — represent the fundamental frequencies of certain piano wires, in vibrations per second, it is impossible to select from them . . . four pairs of notes an octave apart;
683. . . . two combinations of do-mi-sol-do.
684. A frequency somewhere within the usual broadcast band in this country is nearer to 1,000,000 cycles per second than to either 1000 or 1,000,000,000.
685. An important action involved in the reception of music which has been broadcast by radio is . . . amplification;
686. . . . photoelectric action;
687. . . . electric resonance;
688. . . . electromagnetic induction;
689. . . . modulation;
690. . . . television;
691. . . . an action known in a special technical sense as detection.

TRUE-FALSE REVIEW, Continued — (See Page 661)

692. The diaphragm of a radio loud-speaker vibrates in step with the carrier waves characteristic of the station to which the operator has tuned his receiving set.
693. When music is broadcast by radio with the aid of a carbon granule microphone, the microphone . . . generates radio waves;
694. . . . acts as a variable electric resistance controlled by sound waves;
695. . . . generates electric currents;
696. . . . impresses an audio-frequency variation on a direct current supplied at the expense of a source of energy other than the sound waves;
697. . . . is an agency by which the carrier waves are modulated.
698. When the appearance of a face is to be broadcast by radio, the scanning of the face by a means involving photoelectric action accomplishes approximately the same purpose for light that the microphone does for sound.
699. The development of the electronic scanning method of television

has obviated the need of the precise synchronization between sending and receiving apparatus which is characteristic of systems employing rotating disks.

700. One reason why the electronic scanning method of television is an improvement over the early rotating-disk method is that it greatly increases the inertia of the agencies requiring synchronization.

TRUE-FALSE REVIEW: PART 4

(See Unit 4; also, for concluding items, Chapter 18.)

701. Geology includes, as subject matter either wholly or partly geological in nature, all these topics . . . the weather, streams, winds, rain, seasons, erosion, natural drainage, planning of canals;
702. . . . minerals, crystal structure, harbor maintenance, mining, sources of water supply for cities, search for sources of petroleum, drilling for petroleum, testing of sites for the foundations of buildings;
703. . . . earthquakes, history of the earth, radioactivity, volcanic action, glaciers, age of the earth, planetesimal hypothesis.
704. Seasonal changes are due primarily to . . . the wobbling of the earth's axis;
705. . . . the earth's equatorial bulge;
706. . . . changes of the earth's distance from the sun.
707. The angle between the earth's axis and the plane of the earth's orbit is . . . approximately 23.5 degrees;
708. . . . approximately constant over a period of a few years;
709. . . . approximately constant over a period of 50 centuries;
710. . . . equal to the angle between the equator and the tropic of Cancer;
711. . . . equal to the angle between the equator and the tropic of Capricorn;
712. . . . equal to the angle between the equator and the north pole;
713. . . . equal to half the angular width of the torrid zone.
714. At noon June 21, sunlight falls on Lake Michigan more directly (more nearly vertically) than on the Gulf of Mexico.
715. The sun never reaches the zenith (the overhead point) . . . at the equator;
716. . . . at 20 degrees north latitude;
717. . . . at 40 degrees north latitude;

718. . . . at New York;
719. . . . at the north pole.
720. If the earth's axis were always perpendicular to the plane of the earth's orbit, Buenos Aires and New York would both experience a very mild winter during the months of December and January.

TRUE-FALSE REVIEW, Continued — (See Page 661)

721. In July, the number of hours of sunlight in a 24-hour day is greater at Chicago . . . than at New Orleans;
722. . . . than at the north pole;
723. . . . than at the equator;
724. . . . than at Buenos Aires.
725. The primary cause of winds is convection.
726. A great mass of air moving towards the equator tends to be deflected westward if it comes . . . from the northern hemisphere;
727. . . . from the southern hemisphere.
728. The direction of the trade winds would be reversed if the direction of the earth's rotation were reversed.
729. The direction of the trade winds is the same as that of the prevailing westerly.
730. The direction of the Gulf Stream is everywhere the same as that of the trade winds.
731. Some of the clouds visible in the atmosphere are composed of . . . water vapor;
732. . . . small particles of liquid water;
733. . . . small particles of ice.
734. A condition favoring rainfall is . . . the ascent of a mixture of air and water vapor;
735. . . . the cooling of a mixture of air and water vapor;
736. . . . the expansion of a mixture of air and water vapor;
737. . . . the infiltration of dust into a mass of air containing supercooled water vapor.
738. The heat liberated by the condensation of vapor into raindrops promotes an upward motion of the column of air in which the action is taking place.
739. When dew forms on the windowpane of a heated house in winter, it usually forms on the outer surface of the glass.
740. The principal reason why some hailstones are larger than others is that the dust and other particles which serve as nuclei for condensing water vapor are of different sizes.

741. The tops of the highest mountains are about three times as far above sea level as the deepest ocean beds are below it.
742. It is necessary to know the density of the earth's inner core in order to determine the average density of the earth as a whole.
743. The fact that the average density of the whole earth exceeds that of the earth's crust is sure proof . . . that the earth's core is composed of iron and nickel;
744. . . . that the average density of the core exceeds the average for the whole earth.
745. The fact that a great many meteorites are found to consist largely of iron and nickel is sure proof that the earth's core is composed largely of those metals.
746. Tides cannot be observed elsewhere than in bodies of water.
747. The purpose for which the geologist uses the seismograph is to produce earthquakes artificially.
748. The results of at least two different kinds of observations prove that the earth's interior is largely composed of rigid rather than molten material.

TRUE–FALSE REVIEW, Continued — (See Page 661)

749. Granite is classified as . . . an igneous rock;
750. . . . a sedimentary rock;
751. . . . a metamorphic rock.
752. Slate is a metamorphic rock.
753. Limestone is a sedimentary rock.
754. Granite is an excellent conductor of heat.
755. Spalling is a process of weathering.
756. The higher the thermal conductivity of a rock, the greater its susceptibility to spalling.
757. The greater the coefficient of expansion of a rock, the greater its susceptibility to spalling.
758. The spalling of a rock is promoted . . . if it remains very hot all the time;
759. . . . if it remains very cold all the time;
760. . . . if it possesses a polished, highly reflecting surface;
761. . . . if the daily change of temperature, from day to night, is relatively great.
762. The fact that granite is a mixture, not homogeneous, helps to render it susceptible to spalling.
763. Spalling unaided can turn granite into soil.

764. The fact that granite possesses a crystalline nature helps to render it susceptible to disintegration by spalling.
765. Granite is the only kind of rock that is susceptible to spalling.
766. Exfoliation is another name for spalling.
767. Exposed massive rock on the moon's surface must undergo severe spalling.
768. Spalling is promoted . . . by aridity;
769. . . . by the presence of vegetation.

TRUE-FALSE REVIEW, Continued — (See Page 661)

770. Underground water retards chemical weathering by keeping the rocks clean.
771. If drilling to provide an artesian well is to succeed at a given place, the water table there must be higher than in a neighboring region.
772. Clay is formed by the chemical weathering of limestone.
773. Feldspar is one of the components of granite.
774. One product of the chemical weathering of feldspar is the compound of which pure sand is composed.
775. One of the products of the chemical weathering of feldspar is silicon dioxide.
776. One of the feldspars is a silicate of sodium and aluminum.
777. This formula is balanced:

$$CaCO_3 + H_2O + CO_2 \rightleftarrows Ca(HCO_3)_2$$

778. The action represented by the foregoing formula . . . is an example of the geological importance of dissolved carbon dioxide;
779. . . . involves clay;
780. . . . involves limestone;
781. . . . involves one of the most abundant sedimentary rocks;
782. . . . involves one of the most abundant igneous rocks;
783. . . . helps to account for the existence of sinkholes;
784. . . . helps to account for the existence of underground caverns;
785. . . . helps to account for the existence of stalactites;
786. . . . helps to account for the existence of stalagmites;
787. . . . helps to form mines rich in pure calcium.
788. During the evolution of a river, the channel is cut headward rather than seaward.
789. One sign that a river is relatively old, as rivers go, is . . . meandering;

790. . . . numerous waterfalls;
791. . . . an alluvial plain or delta near the mouth;
792. . . . deep gorges;
793. . . . cessation of retreat of the head;
794. . . . extremely rapid flow, as compared with a young river;
795. . . . relatively great annual volume of water transported;
796. . . . relatively great annual transportation of soil.

TRUE–FALSE REVIEW, Continued — (See Page 661)

797. The amount of soil transported annually by severe dust storms in this country is insignificant in comparison with the amount transported by the Mississippi.
798. Deforestation helps to produce both floods and droughts.
799. The five great eras of geological history are arranged in chronological order, most recent first, as follows . . . Cenozoic, Mesozoic, Paleozoic, Proterozoic, Archeozoic;
800. . . . Cenozoic, Paleozoic, Mesozoic, Archeozoic, Proterozoic.
801. If the five great eras are arranged in correct chronological order, most recent first, the same arrangement lists them in order of increasing duration.
802. The Pleistocene was one of the longest of the geological eras.
803. The Pleistocene was characterized by repeated glaciations of what is now northern United States.
804. The age of the earth is *most* reliably determined by a method based on the study . . . of fossils;
805. . . . of the saltiness of the sea;
806. . . . of the rate of erosion of the Mississippi valley;
807. . . . of radioactivity;
808. . . . of biological evolution;
809. . . . of the nebular hypothesis;
810. . . . of the planetesimal hypothesis;
811. . . . of stars;
812. . . . of rate of formation of sedimentary rock;
813. . . . of rate of formation of stratified rock.
814. The Cenozoic is correctly characterized as the era of mammalian dominance.
815. The earliest forms of vegetable life appeared in the Mesozoic era.
816. The Mesozoic is correctly characterized as the era of reptilian dominance.

817. The Mesozoic era was the age of dinosaurs.
818. The Appalachian mountains are younger than the Rockies.
819. The fact that all great mountain ranges occupy the sites of former depressions, or geosynclines, lends support to the ideas of isostasy.
820. Large portions of North America have been inundated by the ocean a number of times.
821. In general, the earth's crust is denser in mountainous regions than under the oceans.
822. The fact that the density of the earth's crust in mountainous regions differs consistently from the density of the crust which underlies the oceans, is satisfactorily accounted for by the leaching of lighter materials out of the mountains by erosion.

TRUE-FALSE REVIEW, Continued— (See Page 661)

823. Gravitational action is central in that explanation of mountain building known as the theory of isostasy.
824. A relatively rapid melting of the present remnants of the Pleistocene ice sheets . . . would not be sufficient to change sea level appreciably.
825. . . . would correctly be expected to produce diastrophic readjustments.
826. That the history of present mountain ranges is not one of continuous erosion from the earliest geological times is attested . . . by measurements of rates of erosion;
827. . . . by drowned valleys;
828. . . . rock faults;
829. . . . earthquakes;
830. . . . distribution of fossils;
831. . . . the nature of certain caves;
832. . . . by outcrops;
833. . . . distribution of stratified rock;
834. . . . distribution of sedimentary rock;
835. . . . by the existence of sinuous rock folds whose crests show relatively little erosion.
836. The failure of the nebular hypothesis . . . has greatly weakened the molten-globe hypothesis of earth history;
837. . . . has necessarily forced abandonment of contraction as one of the possible explanations of mountain-building.
838. All volcanism dates from recent eras.

839. The behavior of several adjacent volcanoes is always such as to support the view that the earth is largely molten beneath a relatively thin outer crust.
840. Volcanic eruptions have occurred in North America within the last century.

TRUE–FALSE REVIEW, Concluded — (See Page 661)

841. The geographical distribution of volcanoes supports the idea that diastrophism and volcanism are not related.
842. The distribution of volcanic effects in time proves that diastrophic changes are due principally to astronomical factors.
843. Both carbon dioxide and volcanic dust help to produce the greenhouse effect.
844. The evidence thus far obtained indicates that, among the factors which might operate to cause ice ages, variations of the amount of volcanic dust in the atmosphere have been more effective . . . than any astronomical factor;
845. . . . than any variations of the density of carbon dioxide in the atmosphere.
846. The trend of geological evolution is such that ice ages are not at all likely ever to come again.
847. The fact that curved space cannot be pictured is sure proof that Einstein's ideas of the nature of the physical universe are unsound.
848. The result of the Michelson-Morley experiment indicates that one star, no matter how fast it traveled away from a second star, could not avoid being overtaken by the light radiated towards it by the second.
849. Observational evidence indicates that radiant energy resembles matter in so far as susceptibility to gravitational effects is concerned.
850. The cyclotron has proved conclusively that elements are being artificially transmuted in the exterior galaxies.

INTERNATIONAL ATOMIC WEIGHTS

1937

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	Symbol	Atomic Number	Atomic Weight		Symbol	Atomic Number	Atomic Weight
Aluminum	Al	13	26.97	Molybdenum	Mo	42	96.0
Antimony	Sb	51	121.76	Neodymium	Nd	60	144.27
Argon	A	18	39.944	Neon	Ne	10	20.183
Arsenic	As	33	74.91	Nickel	Ni	28	58.69
Barium	Ba	56	137.36	Nitrogen	N	7	14.008
Beryllium	Be	4	9.02	Osmium	Os	76	191.5
Bismuth	Bi	83	209.00	Oxygen	O	8	16.0000
Boron	B	5	10.82	Palladium	Pd	46	106.7
Bromine	Br	35	79.916	Phosphorus	P	15	31.02
Cadmium	Cd	48	112.41	Platinum	Pt	78	195.23
Calcium	Ca	20	40.08	Potassium	K	19	39.096
Carbon	C	6	12.00	Praseodymium	Pr	59	140.92
Cerium	Ce	58	140.13	Protactinium	Pa	91	231
Cesium	Cs	55	132.91	Radium	Ra	88	226.05
Chlorine	Cl	17	35.457	Radon	Rn	86	222
Chromium	Cr	24	52.01	Rhenium	Re	75	186.31
Cobalt	Co	27	58.94	Rhodium	Rh	45	102.91
Columbium	Cb	41	92.91	Rubidium	Rb	37	85.44
Copper	Cu	29	63.57	Ruthenium	Ru	44	101.7
Dysprosium	Dy	66	162.46	Samarium	Sm	62	150.43
Erbium	Er	68	167.64	Scandium	Sc	21	45.10
Europium	Eu	63	152.0	Selenium	Se	34	78.96
Fluorine	F	9	19.00	Silicon	Si	14	28.06
Gadolinium	Gd	64	157.3	Silver	Ag	47	107.880
Gallium	Ga	31	69.72	Sodium	Na	11	22.997
Germanium	Ge	32	72.60	Strontium	Sr	38	87.63
Gold	Au	79	197.2	Sulfur	S	16	32.06
Hafnium	Hf	72	178.6	Tantalum	Ta	73	180.88
Helium	He	2	4.002	Tellurium	Te	52	127.61
Holmium	Ho	67	163.5	Terbium	Tb	65	159.2
Hydrogen	H	1	1.0078	Thallium	Tl	81	204.39
Indium	In	49	114.76	Thorium	Th	90	232.12
Iodine	I	53	126.92	Thulium	Tm	69	169.4
Iridium	Ir	77	193.1	Tin	Sn	50	118.70
Iron	Fe	26	55.84	Titanium	Ti	22	47.90
Krypton	Kr	36	83.7	Tungsten	W	74	184.0
Lanthanum	La	57	138.92	Uranium	U	92	238.14
Lead	Pb	82	207.22	Vanadium	V	23	50.95
Lithium	Li	3	6.940	Xenon	Xe	54	131.3
Lutecium	Lu	71	175.0	Ytterbium	Yb	70	173.04
Magnesium	Mg	12	24.32	Yttrium	Y	39	88.92
Manganese	Mn	25	54.93	Zinc	Zn	30	65.38

PERIODIC SYSTEM OF THE ELEMENTS

The italic number at the right of the symbol is the Atomic Number of the element, and the number below is the Atomic Weight to the first place of decimals only.

Group	0	I		II		III		IV		V		VI		VII		VIII		
Type of Oxide Type of Hydride		R_2O RH		RO RH_2		R_2O_3 RH_3		RO_2 RH_4		R_2O_5 RH_3		$R_2O_6(RO_3)$ RH_2		R_2O_7 RH		RO_4		
		A	B	A	B	A	B	A	B	A	B	A	B	A	B			
		H *1* 1.0																
First (short) Period	He *2* 4.0	Li *3* 6.9		Be *4* 9.0			B *5* 10.8		C *6* 12.0		N *7* 14.0		O *8* 16.0		F *9* 19.0			
Second (short) Period	Ne *10* 20.2	Na *11* 23.0		Mg *12* 24.3			Al *13* 27.0		Si *14* 28.1		P *15* 31.0		S *16* 32.1		Cl *17* 35.5			
Third (long) Period	A *18* 39.9	K *19* 39.1	Cu *29* 63.6	Ca *20* 40.1	Zn *30* 65.4	Sc *21* 45.1	Ga *31* 69.7	Ti *22* 47.9	Ge *32* 72.6	V *23* 51.0	As *33* 74.9	Cr *24* 52.0	Se *34* 79.0	Mn *25* 54.9	Br *35* 79.9	Fe *26* 55.8	Co *27* 58.9	Ni *28* 58.7
Fourth (long) Period	Kr *36* 83.7	Rb *37* 85.4	Ag *47* 107.9	Sr *38* 87.6	Cd *48* 112.4	Y *39* 88.9	In *49* 114.8	Zr *40* 91.2	Sn *50* 118.7	Cb *41* 92.9	Sb *51* 121.8	Mo *42* 96.0	Te *52* 127.6	Ma *43* ?	I *53* 126.9	Ru *44* 101.7	Rh *45* 102.9	Pd *46* 106.7
Fifth (long) Period	Xe *54* 131.3	Cs *55* 132.9	Au *79* 197.2	Ba *56* 137.4	Hg *80* 200.6	*57–71	Tl *81* 204.4	Hf *72* 178.6	Pb *82* 207.2	Ta *73* 181.4	Bi *83* 209.0	W *74* 184.0	Po *84* ?	Re *75* 186.3	—*85*	Os *76* 191.5	Ir *77* 193.1	Pt *78* 195.2
Sixth (incomplete) Period	Rn *86* 222.0	—*87*		Ra *88* 226.0		Ac *89* (227)		Th *90* 232.1		Pa *91* (231)		U *92* 238.2						

*** 15 Rare Earths:**

La *57* 138.9	Ce *58* 140.1	Pr *59* 140.9	Nd *60* 144.3	Il *61* ?	Sm *62* 150.4	Eu *63* 152.0	Gd *64* 157.3	Tb *65* 159.2	Dy *66* 162.5	Ho *67* 163.5	Er *68* 167.6	Tm *69* 169.4	Yb *70* 173.0	Lu *71* 175.0

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